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Fast transient numerical simulations with EUROPLEXUS

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Directorate for Space Security and Migration

Safety and Security of Buildings

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European Commission

fast transient dynamics • fluid-structure interaction • multiphysics

Table of content

epx
europlexus software

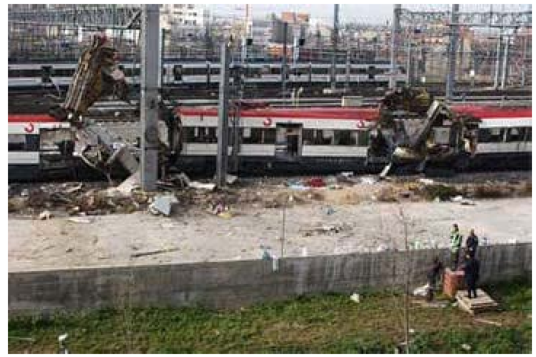
fast transient dynamics • fluid-structure interaction • multiphysics

Introduction (JRC)

European Commission

Terrorism

Paris 2015, 12 fatalities



Madrid 2004, 191 fatalities

New York 2001, 2993 fat.

Ankara 2015, 102 fatalities

[www.timesofisrael.com]

London 2005, 50 fatalities

[wikipedia]

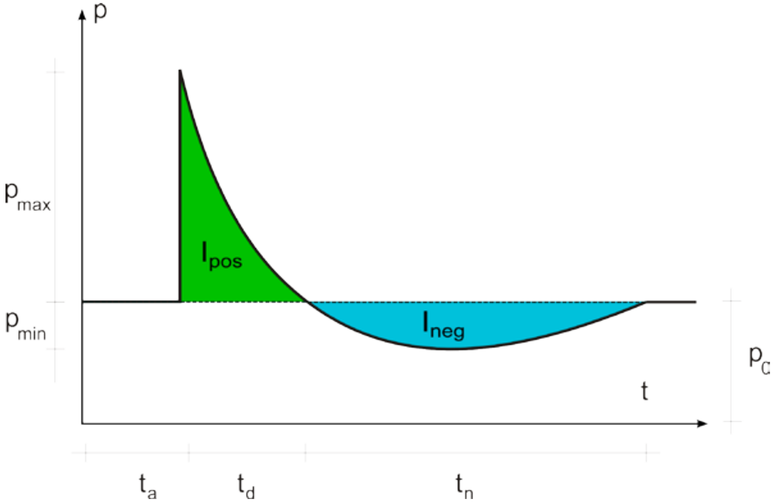
Norway 2011, 77 fatalities

Explosions, Air Blast Waves

- Contact detonations → local failure
- Air blast waves → in general structural failure

[EMI]

Air blast pressure depends on
- the distance
- the size of the explosive



[wikipedia]

Norway 2011, 77 fatalities

Experiments → Model Calibration → **Simulations**

→ ELSA labs

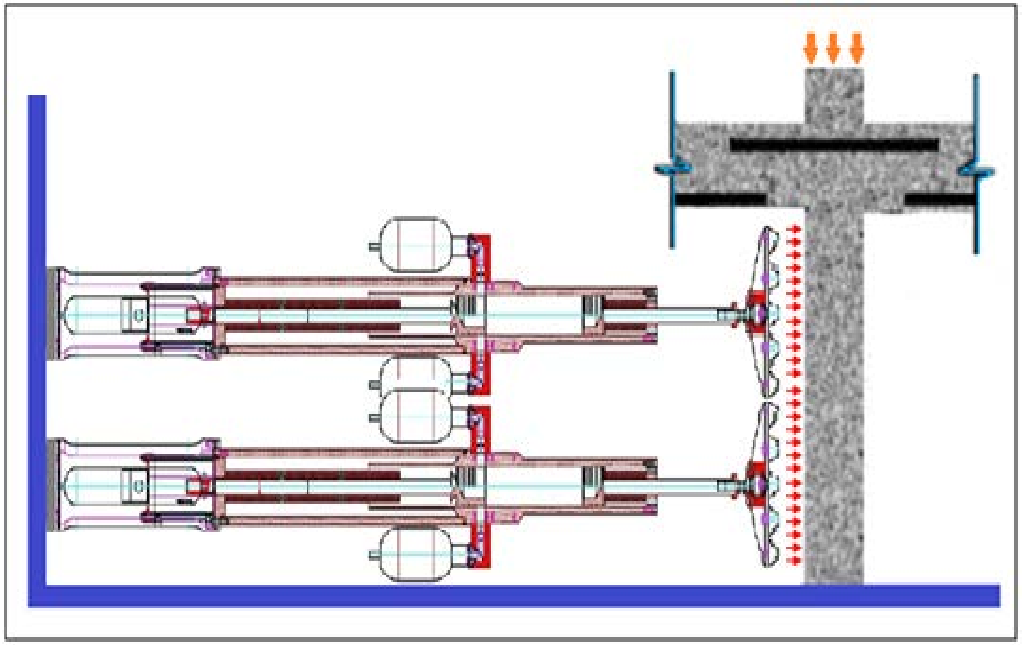
- Experimental setup for fast dynamic testing of materials
- Experimental setup for testing small structures under blast loading

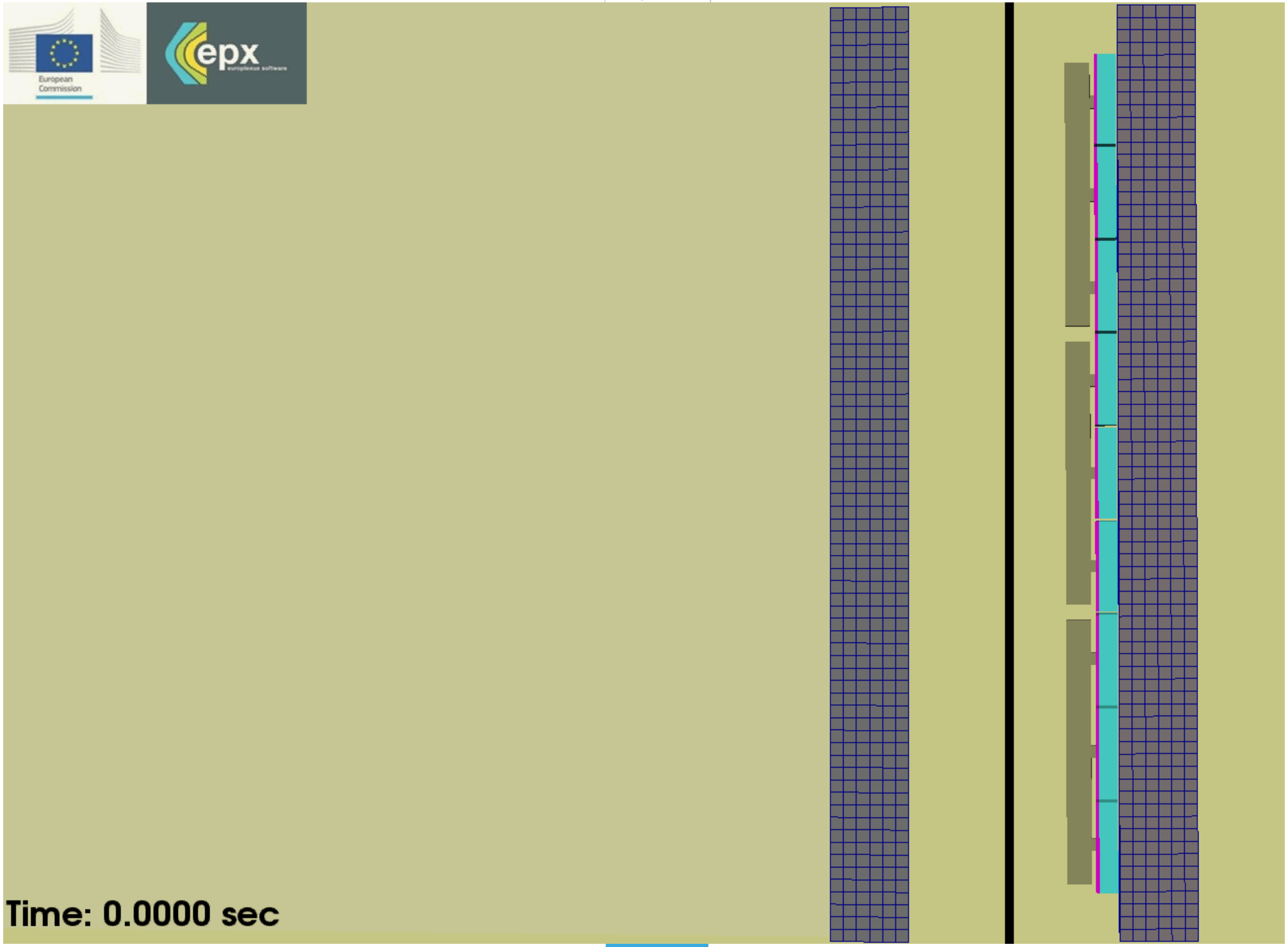
→ **Simulation tool EUROPLEXUS**, developed by JRC and CEA

- Explicit finite element code for fast dynamic response of structures (explosions, impacts, crashes, etc.)
- Specialized in modelling of Fluid-Structure Interaction phenomena
- Experience in simulation of safety problems

EPX EUROPLEXUS Software

Blast Simulator

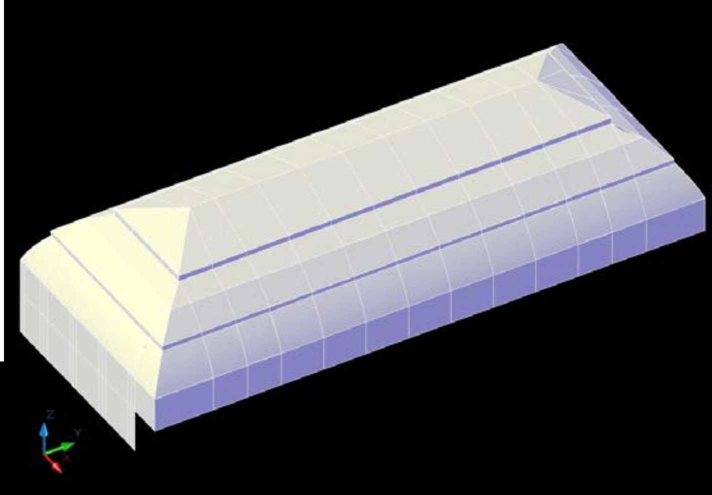


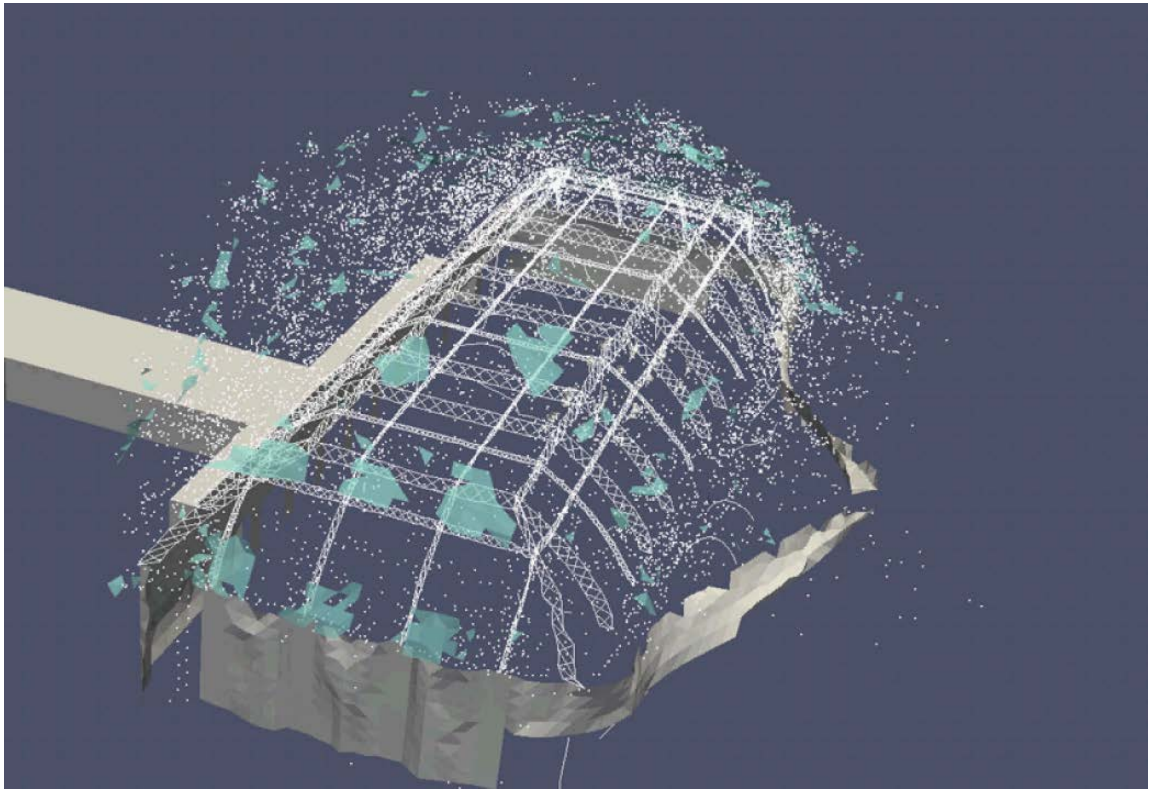


European
epx
Time: 0.0000 sec

Num. Simulation /EPX

Explosion inside a station

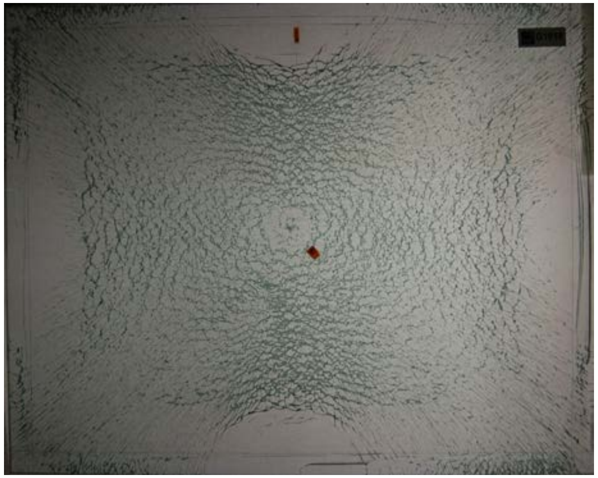


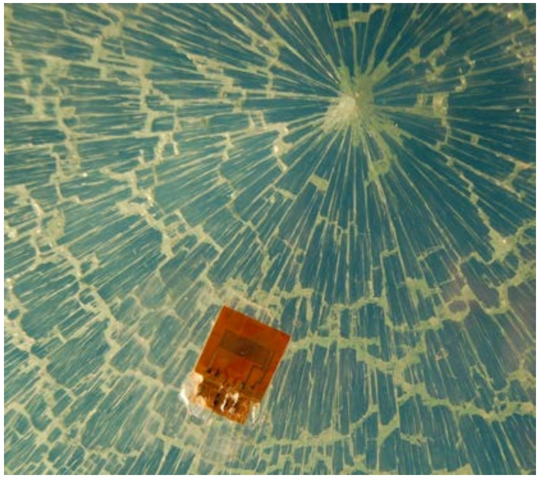


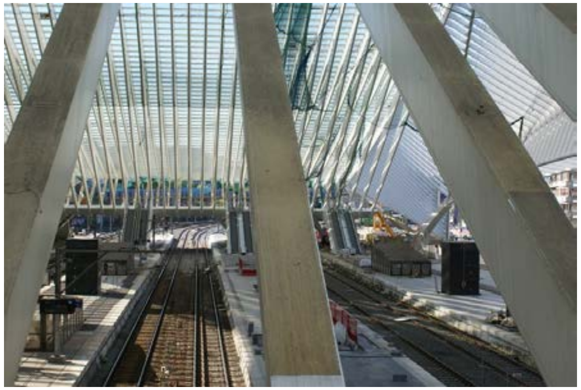
Air blast loading of glass

- Modern architecture uses very often big glass surfaces
- Glass most fragile part of a structure
- Failure results in splinters
- Air blast makes them fly into the building
- Laminated glass could help to hold them together

European Parliament, Strasbourg





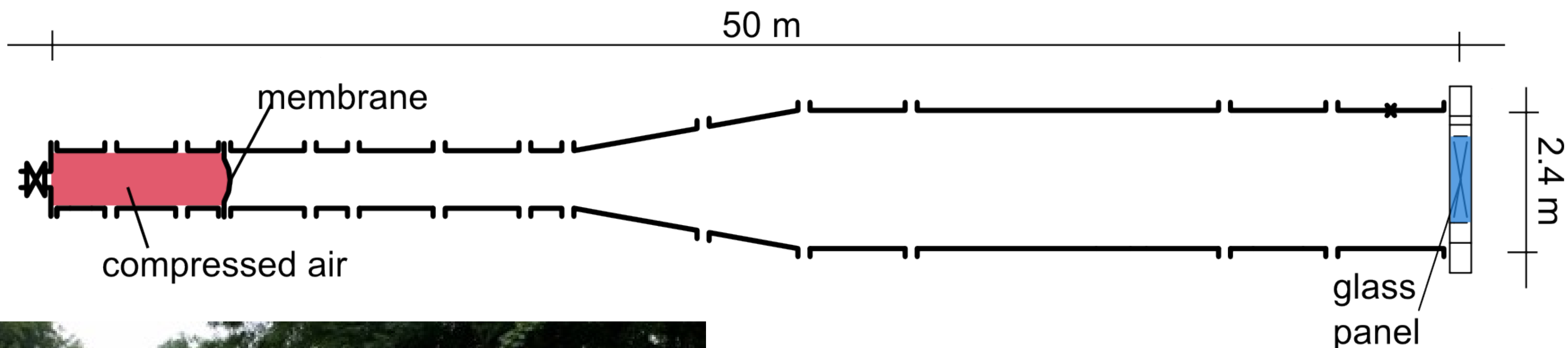


Railway station Liège

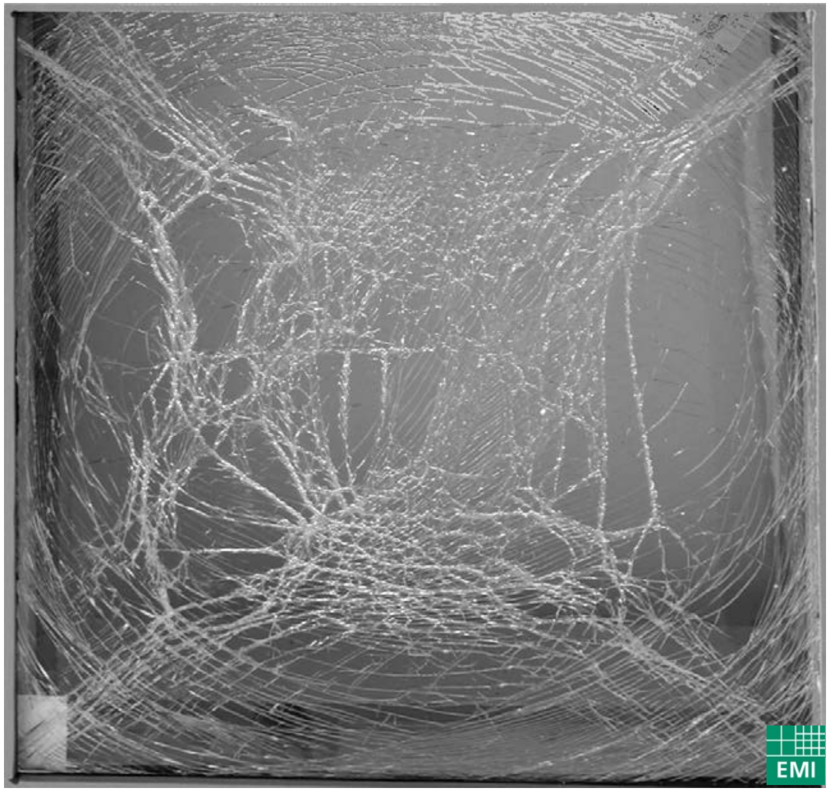
[wikipedia.org]

Experiments

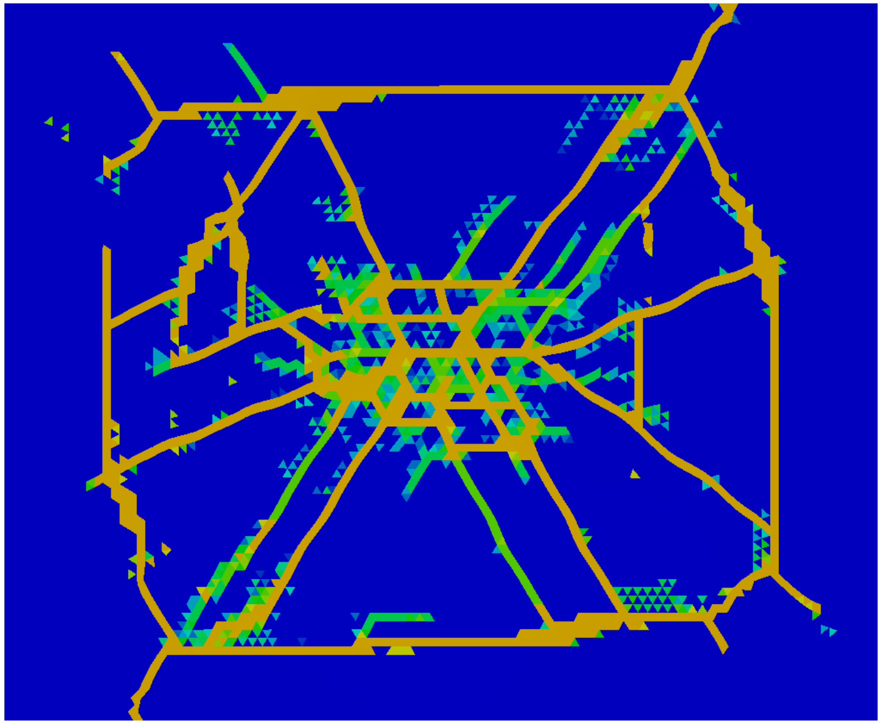
- Full scale test at Ernst-Mach-Institut, Fraunhofergesellschaft, Germany
- Shock tube using compressed air, laminated glass 14 mm thickness
- Overpressures: 82 – 150 kPa (430 – 2300 kg TNT; 40-55 m distance)



Numerical simulation: crack pattern



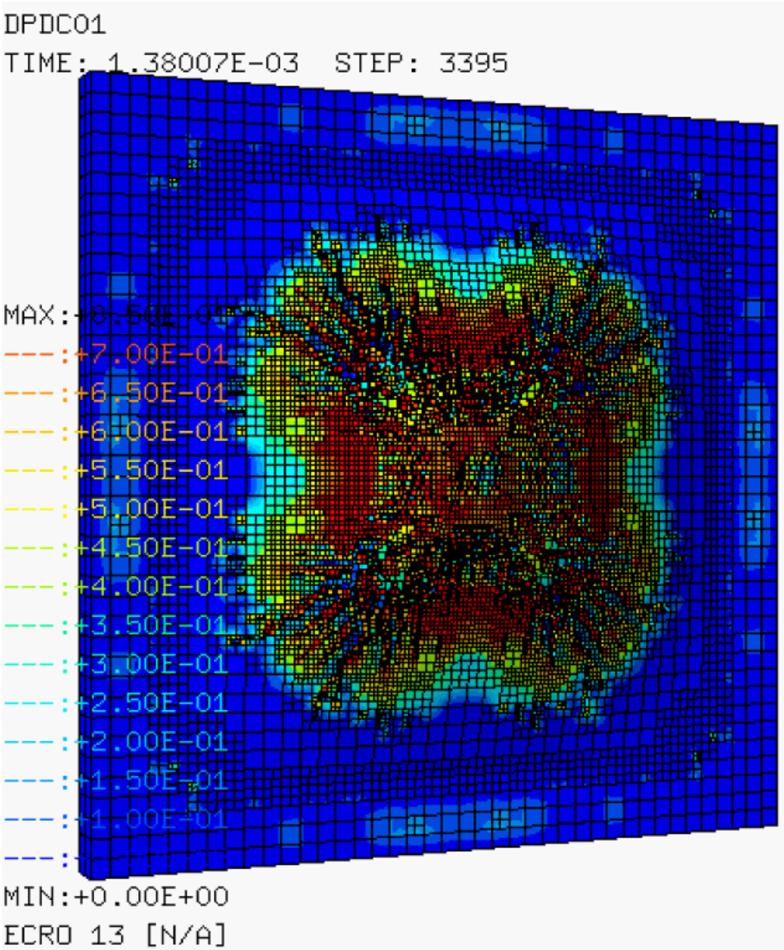
[Kranzer et al. 2005]

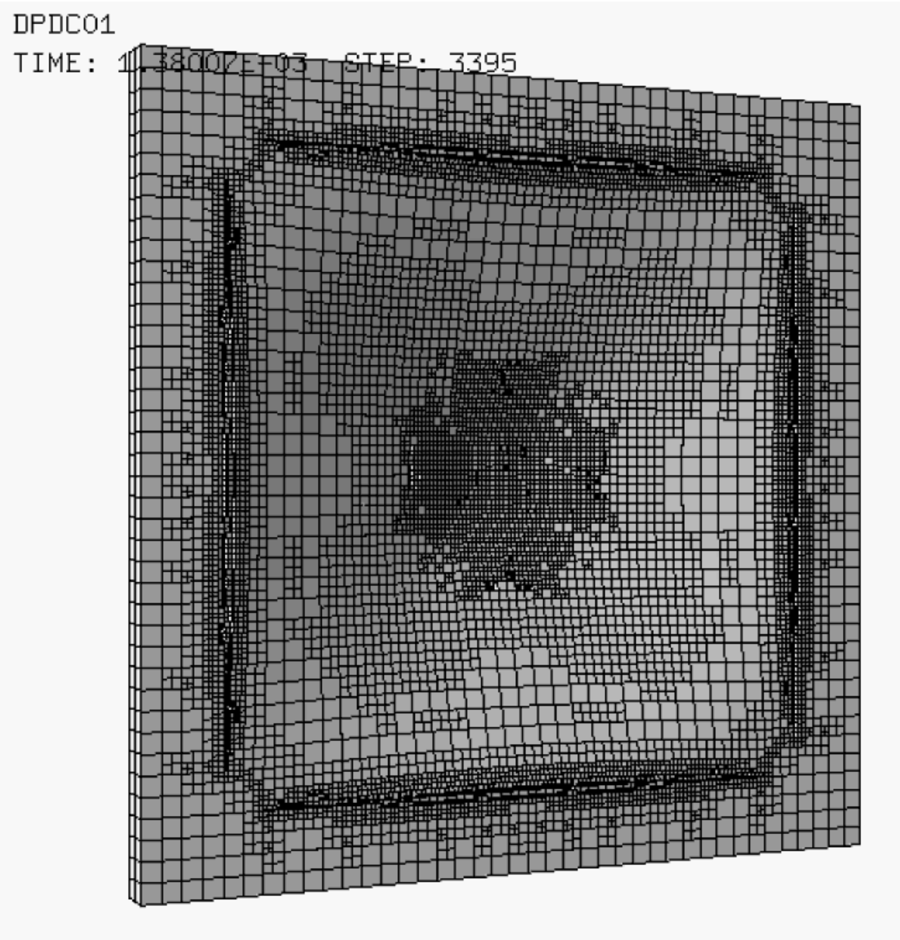


Experiment

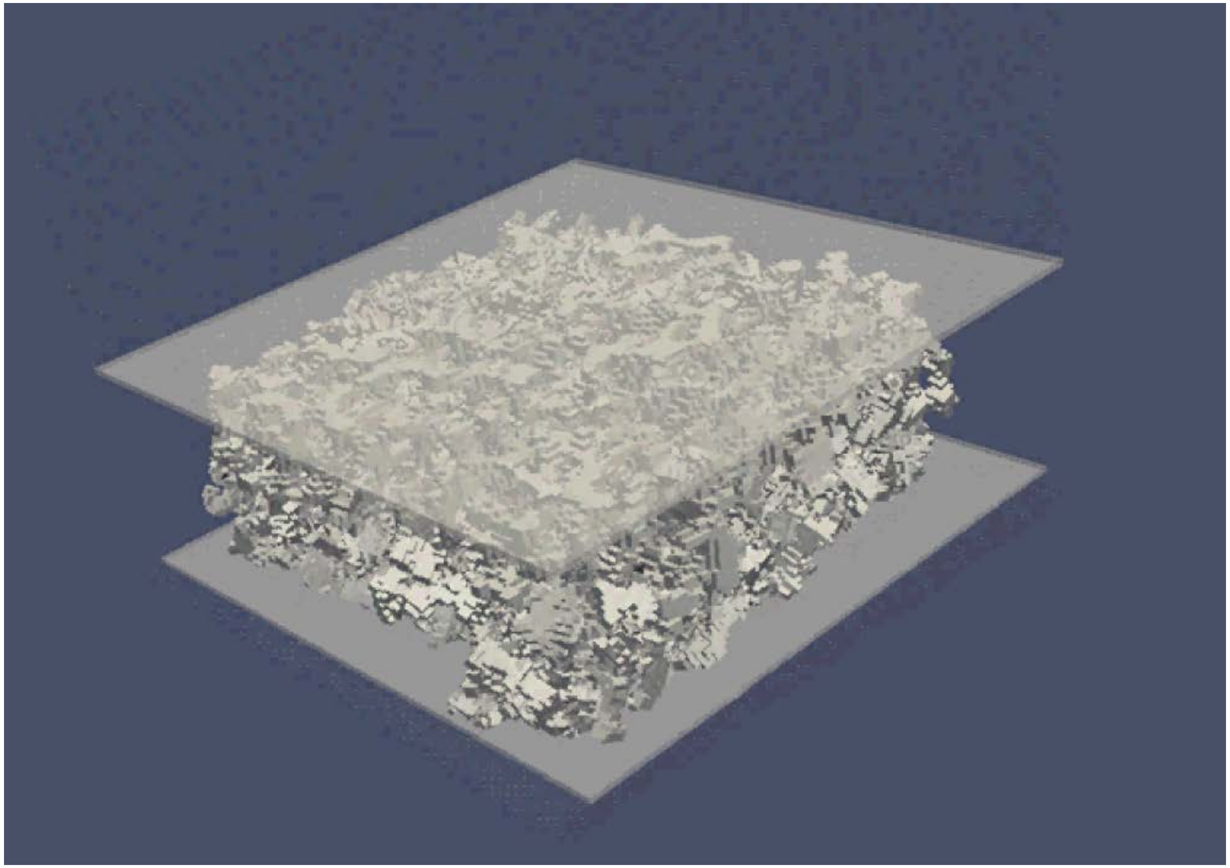
Numerical failure

Adaptivity (concrete)





Aluminium foam



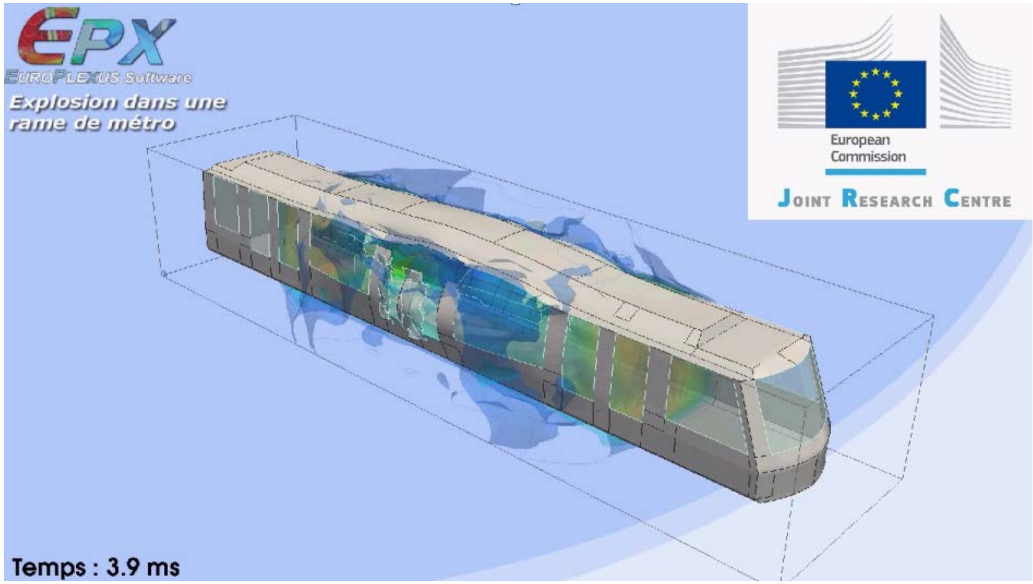
Metal tube

Soft targets

- Unarmored or undefended target (wikipedia)
- Explosions in urban terrain

[www.timesofisrael.com]

Ankara 2015, 102 fatalities



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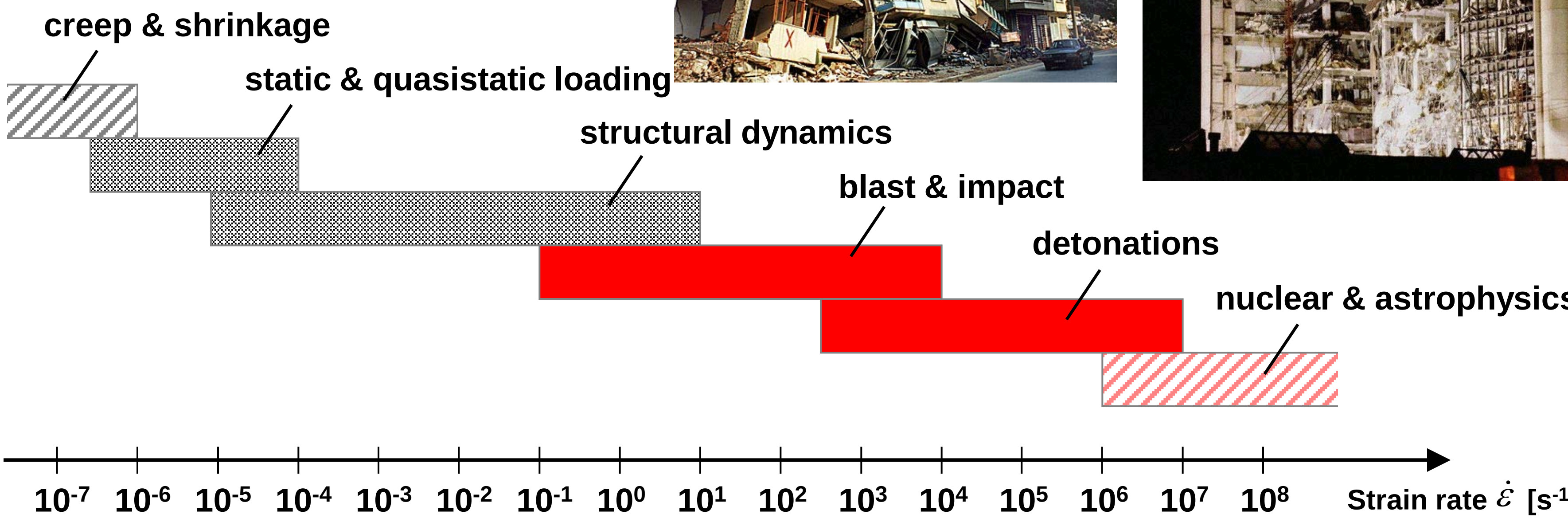
Explicit time integration

Dynamic loadings - Classification

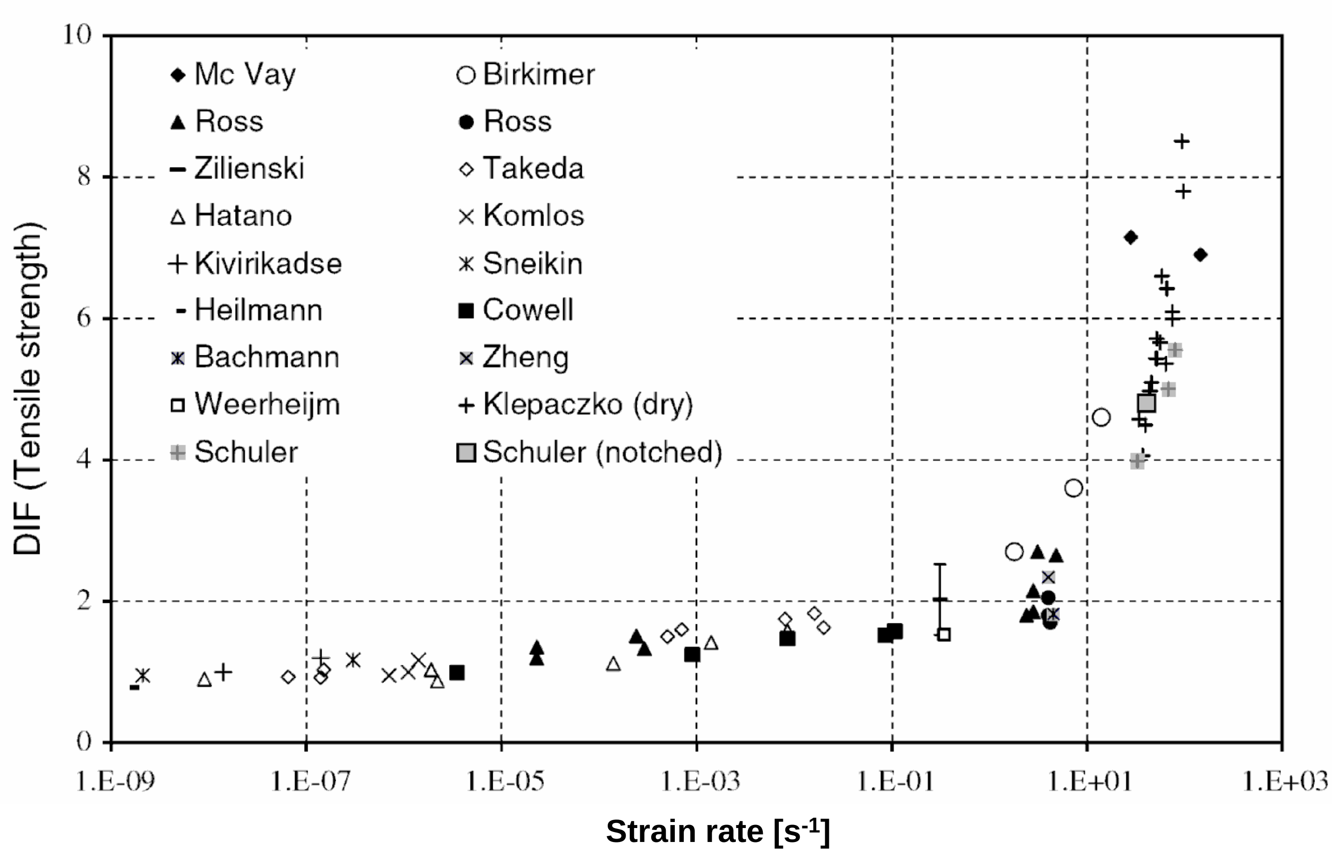


time – strain rate – high pressures – wave propagation

Strain rate behaviour of concrete

Tensile strength

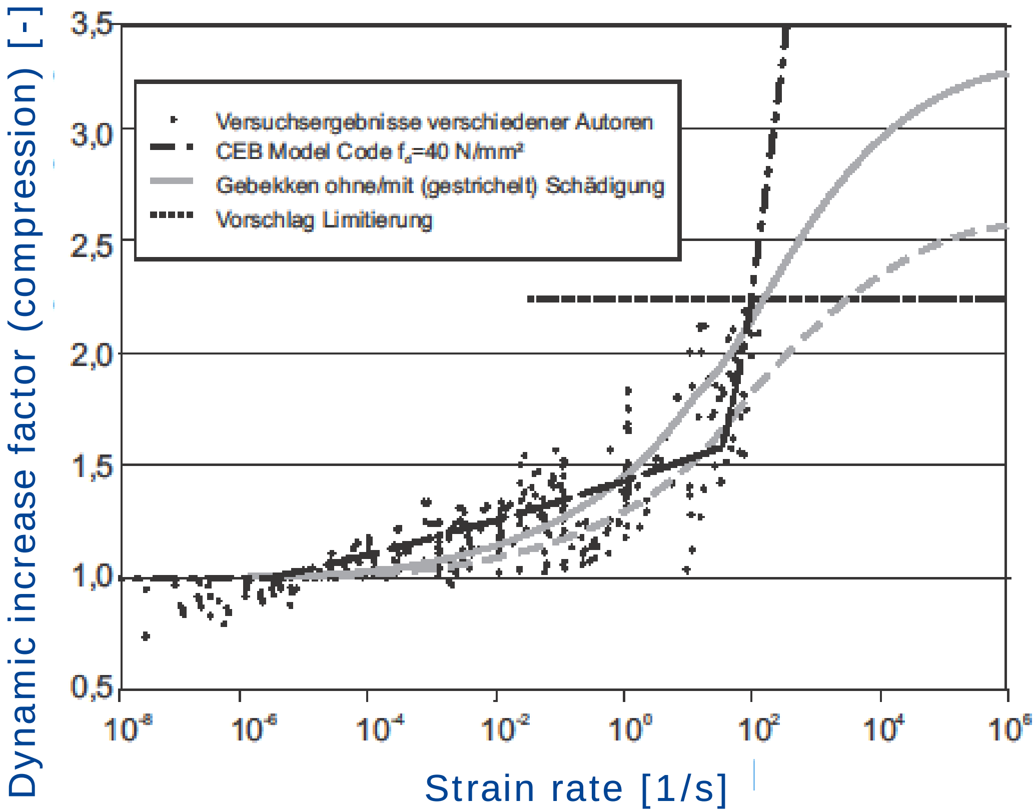
[Schuler 2004]



Strain rate behaviour of concrete

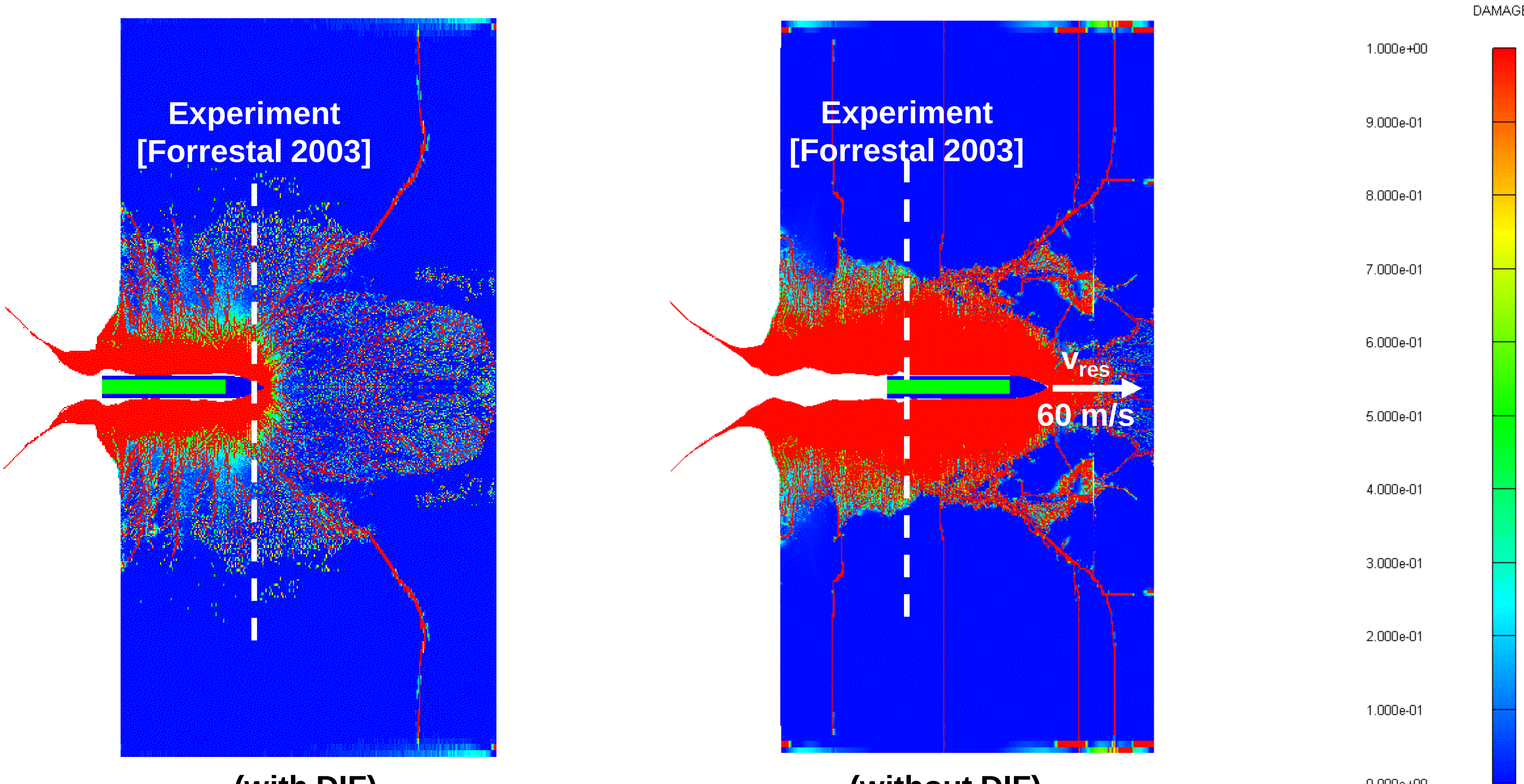
Compressive strength

[Larcher 2007]



Material modelling

Strain rate effects – example: penetration of a concrete target



(with DIF) (without DIF)

Dynamic equations

Newtonian mechanics

F=ma

$$\boldsymbol{M}\boldsymbol{a} + \boldsymbol{C}\boldsymbol{v} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{f}$$

Newmark

$$\boldsymbol{Ma} + \boldsymbol{Cv} + \boldsymbol{Ku} = \boldsymbol{f}$$

Assumption for velocity and displacement:

$$\begin{aligned}
\boldsymbol{v}_{n+1} &= \boldsymbol{v}_n + \Delta t[(1-\gamma)\boldsymbol{a}_n + \gamma \boldsymbol{a}_{n+1}] \\
\boldsymbol{u}_{n+1} &= \boldsymbol{u}_n + \Delta t \boldsymbol{v}_n + \frac{\Delta t^2}{2}[(1-2\beta)\boldsymbol{a}_n + 2\beta \boldsymbol{a}_{n+1}]
\end{aligned}$$

$$\boldsymbol{Ma}_{n+1} + \boldsymbol{Cv}_{n+1} + \boldsymbol{Ku}_{n+1} = \boldsymbol{f}_{n+1}$$

$$(\boldsymbol{M} + \gamma \Delta t \boldsymbol{C} + \beta \Delta t^2 \boldsymbol{K})\boldsymbol{a}_{n+1} = \boldsymbol{f}_{n+1} - \boldsymbol{C}\tilde{\boldsymbol{v}}_{n+1} - \boldsymbol{K}\tilde{\boldsymbol{u}}_{n+1}$$

$$\gamma = \frac{1}{2}, \beta = \frac{1}{4}$$

$$\begin{aligned}
\tilde{\boldsymbol{v}}_{n+1} &= \boldsymbol{v}_n + \Delta t(1-\gamma)\boldsymbol{a}_n \\
\tilde{\boldsymbol{u}}_{n+1} &= \boldsymbol{u}_n + \Delta t \boldsymbol{v}_n + \frac{\Delta t^2}{2}(1-2\beta)\boldsymbol{a}_n
\end{aligned}$$

Explicit Time Integration

$$\beta = 0 \quad \gamma = \frac{1}{2}$$

$$\boldsymbol{a}_{n+1} = \boldsymbol{a}_n + \gamma \Delta \boldsymbol{a}$$

$$\boldsymbol{v}_{n+1} = \boldsymbol{v}_n + \Delta t[(1-\gamma)\boldsymbol{a}_n + \gamma \boldsymbol{a}_{n+1}]$$

$$\boldsymbol{u}_{n+1} = \boldsymbol{u}_n + \Delta t \boldsymbol{v}_n + \frac{\Delta t^2}{2}[(1-2\beta)\boldsymbol{a}_n + 2\beta \boldsymbol{a}_{n+1}]$$

$${}^{t}\boldsymbol{a} = \frac{1}{\Delta t^2}({}^{t-\Delta t}\boldsymbol{u} - 2\,{}^{t}\boldsymbol{u} + {}^{t+\Delta t}\boldsymbol{u})$$

$$\frac{1}{\Delta t^2}\boldsymbol{M}\,{}^{t+\Delta t}\boldsymbol{u} = {}^{t}\boldsymbol{f}_{int} - {}^{t}\boldsymbol{f}_{ext} - \left(\boldsymbol{K} - \frac{2}{\Delta t^2}\boldsymbol{M}\right){}^{t}\boldsymbol{u} - \frac{1}{\Delta t^2}\boldsymbol{M}\,{}^{t-\Delta t}\boldsymbol{u}$$

Solution at t+dt is done with the values at t → balance at time t

No inversion of a matrix

Procedure can be done on element base

Explicit Time Integration

Forward directed method

Advantage

- No equilibrium iterations necessary
- No inversion of the stiffness matrix
- Procedure can be done on element base → MPI

→ Short calculation time

Literature: Belytschko

Disadvantage

- Critical time step length

$$\Delta t \le \alpha_c \frac{d_{\min}}{c}$$

$$0{,}8 \le \alpha_c \le 0{,}98$$

Explicit Time Integration

Many steps but small steps

- → Results from all steps cannot be stored
- → Equilibrium is not given every time step
- → Balance must not be given in a certain time step: contact, erosion ... are easier or possible
- → Boundary conditions needs special care (shown later on)
- → Time step size is critical – check the results

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fast transient dynamics • fluid-structure interaction • multiphysics

EUROPLEXUS introduction

European Commission

EUROPLEXUS History

Development in cooperation between JRC, CEA

Major partner: EDF, ONERA

CASTEM/PLEXUS – CEA (Saclay, France): 1978

Collaboration EU:JRC (Ispra, Italy)/ CEA:1982

- FLUID-STRUCTURE interaction
- ALE method
- PLEXIS-3C : 1986

EUROPLEXUS project

- Merging of codes 1999
- CEA – JRC

EUROPLEXUS Licenses / principles

- Export control
- Distribution by CEA (http://www-epx.cea.fr/)
- Light version (20k stru and 200k flui), downloadable
- Education and Research: free after signing a contract, also parts of the source for further developments
- Commercial license

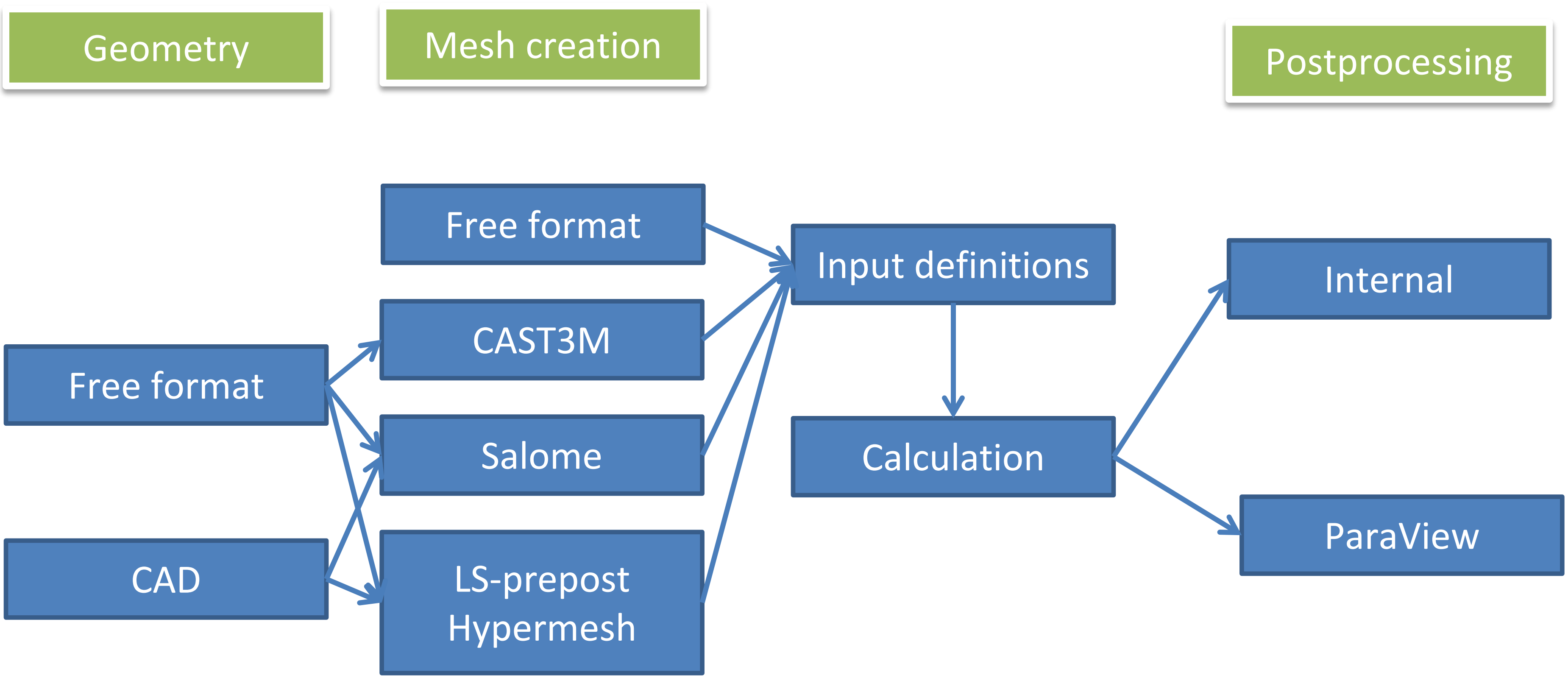
General workflow

Mesh creation → Input definitions → Calculation → Post processing

Mesh creation	Input definitions	Calculation	Post processing
• Nodes • Elements • Groups of nodes/elements	• Materials • Boundaries • Loading • Options	• Reading mesh and input • Producing output	• Visualizing results

- Mesh and inputs separated
- Calculation: exe

Detailed workflow



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Preprocessors

Objective: Create mesh (nodes, elements, groups)

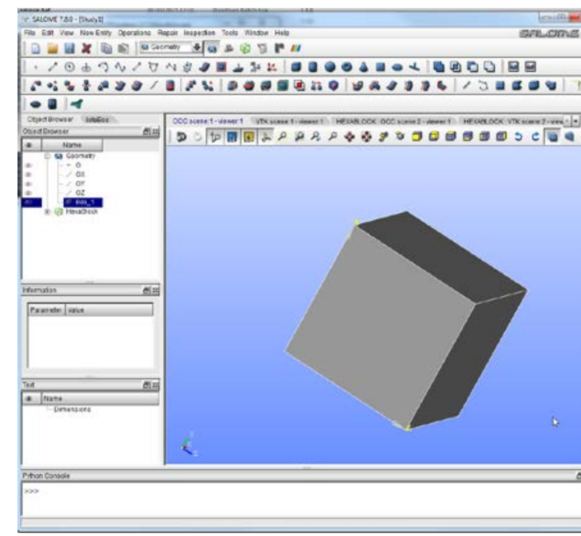
.msh

CAST3M

- FE software (CEA), freely available
- Mesh created by defining points, lines, surfaces etc. (script language)
- Very powerful but difficult to learn

Salome

- generic platform for Pre- and Post-Processing (open-source)



.k

LS-prepost
Hypermesh

- Generic LS-DYNA k-file input

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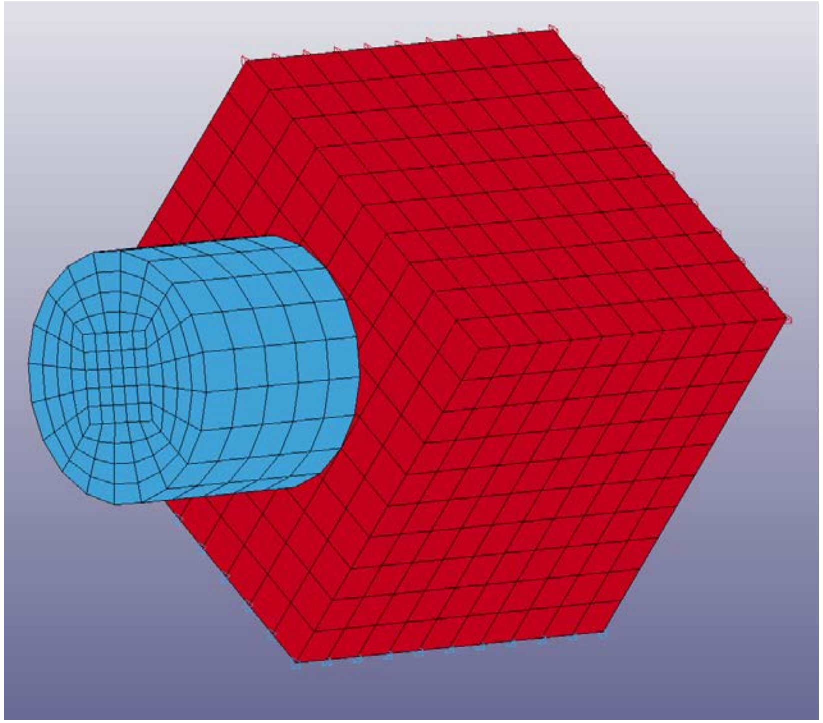
LS-prepost

- Free
- Easy to learn
- Also tool to check k-files

➔ Excursе: How to create mesh with ls-prepost



Organization of k-file

The following keywords are supported

- *NODE
- *ELEMENT_SHELL
- *ELEMENT_SOLID
- *SET_NODE_LIST
- *SET_NODE_ELEM

Postprocessors

Objective: visualize results (displacements, stress,...)

Internal

Listing

Plots

Movies

- Very powerful but more difficult to learn

External

ParaView

- generic platform for Post-Processing (open-source)

Files

.epx	EUROPLEXUS input file
.k	LS-DYNA mesh file
.msh	CASTEM mesh file
.listing	General outputs
.std	Error messages
.log	Logging (one line per step)

EPX-Input file

- *.epx file
- Using groups of keywords (primary keywords)
- Creating epx-file: running through the groups

A	DIME	PROBLEM TYPE AND DIMENSIONING
B	GEOM	MESH AND GRID MOTION
C	COMP	GEOMETRIC COMPLEMENTS
C1	MATE	MATERIALS
D	LINK	LINKS
E	INIT	FUNCTIONS AND INITIAL CONDITIONS
F	CHAR	LOADS
G	ECRI	PRINTOUT AND STORAGE OF RESULTS
H	OPTI	OPTIONS
I	CALC	TRANSIENT CALCULATION DEFINITION
ED		POST-TREATMENT BY EUROPLEXUS
O		INTERACTIVE COMMANDS
V		The built-in OpenGL Graphical Visualizer

Manual

http://europlexus.jrc.ec.europa.eu/public/manual_pdf/manual.pdf
(development version!)
or including in the distribution

EUROPLEXUS

A Computer Program for the Finite Element Simulation of Fluid-Structure Systems under Transient Dynamic Loading

USER'S MANUAL

JRC89891

Commissariat à l'énergie atomique
Direction de l'énergie nucléaire
Département de Modélisation des Systèmes et Structures
Service des Etudes Mécaniques et Thermiques
Laboratoire d'Etudes de Dynamique

European Commission
Joint Research Centre
Directorate for Space, Security and Migration
Safety and Security of Buildings

Contains
- Getting started
- Keyword groups (A-...)
- Bibliography
- Index

→ Hands on!

Units

- User defines the units in a coherent way
- Some exceptions for some materials / models
- SI units strongly recommended (m, kg, s, K)

First file!

```
impact0                                 !title of the problem
ECHO                                    !Output on the console
KFIL                                    !mesh file definition (k-file with name impact0.k)
TRID LAGR                               !3d structural calculation
GEOM Q4GS PART 1 PART 2 TERM            !element definition
COMP EPAI 2 LECT PART 1 TERM            !Thickness of part 1
          5 LECT PART 2 TERM            !Thickness of part 2
MATE LINE RO 7800 YOUN 2.E11 NU 0.3     !Material definition: linear material
          LECT PART 1 PART 2 TERM       !for parts 1 and 2
LINK COUP                               !Links (coupled)
     BLOQ 123 LECT NSET 4 NSET 5 TERM   !Boundaries
INIT VITE 3 -110 LECT PART 2 TERM       !Initial conditions
ECRI FICH PVTK TFRE 1.0E-3              !Output as paraview
               VARI DEPL                !Output variable displacement
OPTI NOTE LOG 1                         !Log file written each step
     CSTA 0.5                           !Stability step
CALC TINI 0.0 TFIN 100.E-3              !Start and end time of calculation
FIN

```

Groups not covered here:

DIME, CHAR

ParaView

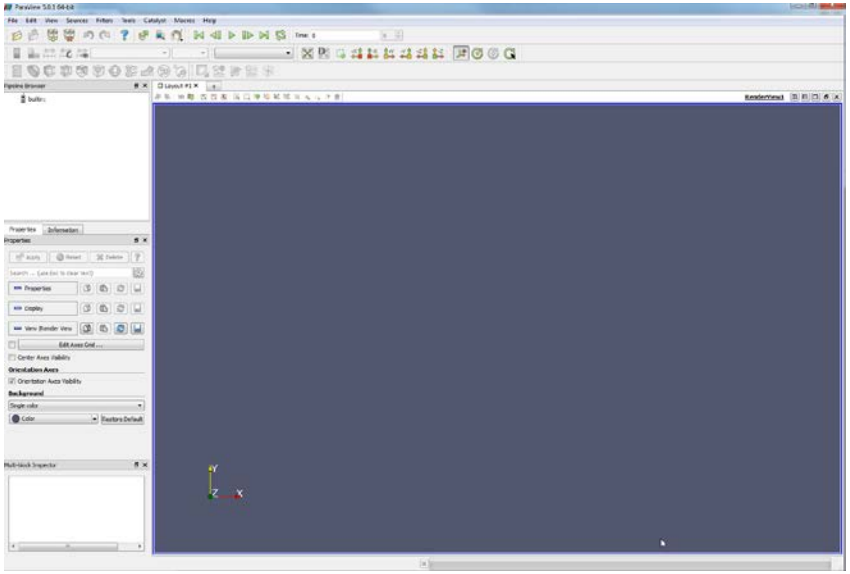
- open source
- multiple-platform
- interactive, scientific visualization
- client–server architecture
- built on top of the Visualization Toolkit (VTK) libraries
- www.paraview.org

ParaView

Export in EPX via ECRI

- ECRI FICH PVTK TFRE 5.E-5
  GROUP AUTO
  VARI DEPL VITE ACCE FEXT FINT ECRO
- vtu files were generated per block and per output step
- pvd file combines them → could be read in ParaView

→ Let’s play with it!



Materials

- Europlexus manual

  8 GROUP C1—MATERIALS

- **MATE** command

```
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75
          PINI 0.5E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75
          PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     CLVF INFI RO 1.189 PRES 1.e5 GAMA 1.4 LECT abso TERM
```

Fluid

Structural

Absorbing

Materials

NUMBER OF ELEMENTS TYPE	156
NUMBER OF MATERIALS TYPE	123

Material-Element combinations (from manual)

```
AVAILABLE MATERIALS FOR EACH ELEMENT
====================================

NO. | ELEMENT | AVAILABLE MATERIALS
----|---------|---------------------------
  1 |  COQU   | LINE PARF ISOT TETA DYNA ORTH
  2 |  TRIA   | LINE PARF ISOT TETA POST FLUI CAVI GAZP NAH2 BETO
    |         | DRUC DYNA EAU  LIQU SOUR MULT FLFA STGN ADCR VM23
    |         | PUFF ORTH JWL  CHOC ADCJ RSEA CRIT BUBB JWLS ZALM
    |         | LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU DRPR VMSF DPSF
    |         | CAMC CLAY SGMP ENGR VPJC
  3 |  BARR   | LINE PARF ISOT DYNA
  4 |  PONC   | LINE PARF ISOT
  5 |  MEMB   | LINE
  6 |  CUBB   | LINE PARF ISOT DPDC
  7 |  CL2D   | IMPE CLVF IMPV
  8 |  CAR1   | LINE PARF ISOT TETA POST FLUI CAVI GAZP NAH2 BETO
    |         | DRUC DYNA EAU  LIQU SOUR MULT FLFA STGN ADCR VM23
    |         | DONE PUFF ORTH JWL  CHOC ADCJ RSEA CRIT BUBB JWLS
    |         | ZALM LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY SGMP VPJC
  9 |  CAR4   | LINE PARF ISOT TETA POST FLUI CAVI GAZP BETO DRUC
    |         | DYNA EAU  MULT FLFA STGN VM23 DONE PUFF ORTH GLAS
    |         | CHOC ADCJ CRIT BUBB LSGL ZALM LMC2 LEM1 BOIS VMJC
    |         | VMZA VMLP VMLU DRPR VMSF DPSF CAMC CLAY HYPE ENGR
    |         | VPJC
 10 |  COQC   | LINE PARF ISOT ORTH
 11 |  CUBE   | LINE ISOT TETA FLUI GAZP NAH2 DRUC DESM DYNA BLMT
    |         | EAU  LIQU SOUR MULT FLFA STGN ADCR VM23 PUFF ORTH
    |         | ORTE GLAS ORTS JWL  CHOC ADCJ RSEA ORPE CRIT BUBB
    |         | LSGL JWLS ZALM LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU
    |         | DRPR VMSF MAZA DPSF CAMC CLAY FOAM HYPE PBED TVMC
    |         | SLZA CRTM SGMP EOBT DADC DPDC BDBM VPJC ORTP
 12 |  COQ3   | LINE ISOT TETA DYNA MCOU CHAN
 13 |  CUB6   | LINE ISOT TETA FLUI GAZP DRUC DYNA BLMT MULT STGN
    |         | VM23 PUFF ORTH ORTE GLAS ORTS CHOC ORPE CRIT LSGL
    |         | BOIS VMJC DRPR VMSF DPSF CAMC CLAY FOAM HYPE SLZA
    |         | CRTM VPJC
 14 |  COQ4   | LINE ISOT TETA DYNA MCOU CHAN
```

```
AVAILABLE ELEMENTS FOR EACH MATERIAL
====================================

E AFTER MATERIAL INDICATES ERODIBLE.

NO. | MATERIAL| AVAILABLE ELEMENTS
----|---------|---------------------------
  1 |  LINE E | COQU TRIA BARR PONC MEMB CUBB CAR1 CAR4 COQC CUBE
    |         | COQ3 CUB6 COQ4 POUT BR3D PR6  TETR TUYA PRIS PMAT
    |         | CUB8 QPPS CMC3 T3GS BILL DST3 DKT3 SHB8 XCUB XCAR
    |         | PROT SPHC Q4G4 MS24 S24  MS38 S38  Q4GR Q4GS INT4
    |         | INT6 INT8 ASHB COQ2 Q4MC T3MC P3ZT TYVF
  2 |  PARF E | COQU TRIA BARR PONC CUBB CAR1 CAR4 COQC BR3D XCUB
    |         | XCAR
  3 |  HILL   | PR6  TETR PRIS CUB8 DST3 Q4GR Q4GS Q4MC T3MC P3ZT
  4 |  ISOT E | COQU TRIA BARR PONC CUBB CAR1 CAR4 COQC CUBE COQ3
    |         | CUB6 COQ4 POUT BR3D PR6  TETR TUYA PRIS CUB8 QPPS
    |         | CMC3 T3GS BILL DST3 DKT3 SHB8 XCUB XCAR PROT SPHC
    |         | Q4G4 Q4GR Q4GS ASHB COQ2 Q4MC T3MC P3ZT TYVF
  5 |  TETA E | COQU TRIA CAR1 CAR4 CUBE COQ3 CUB6 COQ4 PR6  TETR
    |         | PRIS CUB8 T3GS DST3 Q4GR Q4GS COQ2
  6 |  POST   | TRIA CAR1 CAR4
  7 |  FLUI   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR TUBE TUYA BIFU
    |         | CAVI PRIS CUB8 QAX1 TUBM PFEM TUYM T3VF Q4VF CUVF
    |         | PRVF TEVF PYVF TUVF TYVF BIVF CAVF
  8 |  CAVI   | TRIA CAR1 CAR4
  9 |  GAZP   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR TUBE TUYA BIFU
    |         | CAVI PRIS CUB8 QAX1 TUBM TUYM T3VF Q4VF CUVF PRVF
    |         | TEVF PYVF TUVF TYVF BIVF CAVF
 10 |  NAH2   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI PRIS TUBM
    |         | TUYM
 11 |  BETO E | TRIA CAR1 CAR4 PR6  CMC3
 12 |  DRUC E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8
 14 |  IFS    |
 15 |  DESM   | CUBE PR6  TETR PRIS CUB8
 16 |  IMPE   | CL2D CL3D CL1D CL3T CLTU CL23 CL2S CL3S CL32 CL33
    |         | CL22 CL3I CLD3 CLD6 CL3Q CL92 CL93
 18 |  ODMS   | CUB8 XCUB
```

European Commission

Materials

NUMBER OF ELEMENTS TYPE	156
NUMBER OF MATERIALS TYPE	123

number	name	ref	law of behaviour
74	ABSE		
21	CLVF	7.8.33	Boundary conditions for finite volumes
109	DADC	7.6.16	Dynamic Anisotropic Damage Concrete
111	DPDC	7.6.17	dynamic plastic damage concrete
87	DPSF	7.6.41	Drucker Prager with softening and viscoplastic regularization
83	DRPR	7.6.50	Drucker Prager Ispra model
12	DRUC	7.6.6	Drucker-Prager
19	DYNA	7.6.7	dynamic Von Mises isotropic rate-dependent
17	FANT	7.6.29	phantom: ignore the associated elements
9	GAZP	7.7.4	perfect gas
118	GGAS	7.7.1	generic ideal gas material
116	GLIN	7.6.3	generic linear material
117	GPLA	7.6.4	generic plastic material
48	GVDW	7.7.27	Van Der Waals gas
40	GZPV	7.7.23	perfect gas for Van Leer
95	HYPE	7.6.53	hyperelastic material (Model of Mooney-Rivlin, Hart-Smith and Ogden)
4	ISOT	7.6.7	isotropic Von Mises
108	JCLM	7.6.64	Johnson-Cook with Damage Lemaitre-Chaboche for SPHC
50	JWL	7.7.20	explosion (Jones-Wilkins-Lee model)
66	JWLS	7.7.28	Explosion (Jones-Wilkins-Lee for solids)
72	LEM1	7.6.9	Von Mises isotropic coupled with damage (type Lemaitre)
1	LINE	7.6.1	linear elasticity
23	LIQU	7.7.14	incompressible (or quasi-) fluid
70	LMC2	7.6.11	Von Mises isotropic coupled with damage (Lemaitre) with strain-rate sensitivity
26	MASS	7.6.28	mass of a material point
85	MAZA	7.6.15	Mazars-linear elastic law with damage
2	PARF	7.6.7	perfectly plastic Von Mises
125	RIGI	7.6.66	Rigid material (for rigid bodies)
99	SLZA	7.6.55	Steinberg-Lund-Zerilli-Armstrong
35	VM23	7.6.37	Von Mises elasto-plastic radial return
2/4/5/19	VMIS	7.6.7	Von Mises materials
76	VMJC	7.6.46	Johnson-Cook
78	VMLP	7.6.47	Ludwig-Prandtl
79	VMLU	7.6.48	Ludwik
84	VMSF	7.6.40	Von Mises with softening and viscoplastic regularization
77	VMZA	7.6.49	Zerilli-Armstrong
120	VPJC	7.6.65	visco-plastic Johnson-Cook
67	ZALM	7.6.10	Zerilli-Armstrong with damage Lemaitre-Chaboche

Materials (input)

```
"CDEM"   "TINI" tini    "PINI"  pini  <"PREF" pref>
   ...   "KSI0" ksi0   "K0" k0
   ...   "TMAX" tmax    "R" rgas
   ...   "NESP" nesp    "ORDP" ordp    "NLHS" nlhs
   ...
   ...   "COMP1"
   ...   "MMOL"  mmol    "H0" h0    "CREA" crea
   ...   "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
   ...   "YMAS" ymas
   ...
   ...   . . .
   ...
   ...   "COMPnesp"
   ...   "MMOL"  mmol    "H0" h0    "CREA" crea
   ...   "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
   ...   "YMAS" ymas
   ...
   ...   <"KOF" kof>
   ...   <"UCDS" ucds>
   ...   <"DIRE" dire>
   ...   <"TO  " temp0>
   ...   <"H   " hcoef>
   ...   <"GX  " gx>
   ...   <"GY  " gy>
   ...   <"GZ  " gz>
   ...   <"CFLA" 1  "SL  "  sl  "PSL " psl "TSL " tsl
          "DL " dl  "LE  " le  "PU  " pu
          "XIG " xig  "YIG " yig "ZIG " zig>
   ...   <"CFLA" 2  "SL  "  sl  "PSL " psl "TSL " tsl
          "DL " dl  "LE  " le  "A   " acoef "B   " bcoef
          "RO " r0  "XIG " xig  "YIG " yig "ZIG " zig>
 /LECT/
```

```
 "GAZP"  "RO"  rho  "GAMMA"  gamma  "PINI"  pini  <"VISC" mu > ...
        ... < "CV"  cv >  < "PREF"  pref >   /LECTURE/
```

```
"JWLS"  "RO"  rho  <"ROS" ros>   "PINI"  pini  <"PREF"  pref>   ...
   ...  "A"   a      "B"   b      "R1"   r1      "R2"   r2        ...
   ...  "OMEG" omeg    "EINT"  eint   <"BETA"  beta  >          ...
   ...  < "D"   d    "XDET" xdet "YDET" ydet  <"ZDET" zdet> >     ...
   ...  <"EAFT" eaft "CONF" conf "CHAR" char "TSTA" tsta "TEND" tend>  ...
   ...     /LECTURE/
```

```
"VM23"   "RO" rho   "YOUN" young   "NU" nu   "ELAS" sige ...
           <"FAIL" $[ VMIS ; PEPS ; PRES ; PEPR ]$ "LIMI" limit>
           "TRAC" npts*(sig eps)
           /LECTURE/
```

```
"VPJC"   "RO" rho "YOUN" young "NU" nu "ELAS" elas
       <"TOL" tol "MXIT" mxit>
        "QR1" qr1 "CR1" cr1 "QR2" qr2 "CR2" cr2
        "PDOT" pdot "C" c
        "TQ" tq "CP" cp <"TR" tr> "TM" tm "M" m
        "DC" dc "WC" wc
       <"SOLU" solu>
        /LECTURE/
```

```
"DPDC"   "RO" rho     "YOUN" young   "NU" nu     "FC" fc
         "DAGG" dagg
          <"GFT" gft       "GFC" gfc       "GFS" gfs>
          <"PWRC" pwrc>   <"PWRT" pwrt>
          <"B" b>         <"D" d>
          <"OVEC" overc>   <"OVET" overt>   <"SRAT" srate>
          <"R" r>         <"XO" xo>       <"W" w>
          <"D1" d1>       <"D2" d2>       <"PMOD" pmod>
          <"TXCA" txca "TXCT" txct "TXCL" txcl "TXCB" txcb>
          <"FTR"  ftr  "FBCR" fbcr "I1CR" i1cr "RJCR" rjcr>
          <"TXEA" txea "TXET" txet "TXEL" txel "TXEB" txeb>
          <"NC" nc "NOC" noc>     <"NT" nt "NOT" not>
          <"REPW" repow>   <"RECO" recov>
          <"PRED" pred>   <"COPP" copp>  <"EXCT" excent>
          <"VERS" vers>
          <"EFVI">
          <"EROD" <"ENDT" endt> <"ENDC" endc> <"DVOL" dvol>>
           /LECTURE/
```

```
"HYPE"
"TYPE"      4
"RO"        rho
"C01"       c1
"C02"       c2
"C03"       c3
"C04"       c4
"C05"       c5
"C06"       c6
"C07"       c7
"C08"       c8
"BULK"      K
/LECTURE/
```

European Commission

Materials (types)

- **Structural**
  - Brittle (DPDC)
  - Ductile (VM23, VPJC,VMIS ISOT)
  - Hyperelastic (HYPE)

- **Fluid**
  - Perfect gas (GAZP)
  - Detonation in gas mixture (GAZD, CDEM)
  - Water (FLUI, ADCR, SGMP)
  - EOS Jones-Wilkins-Lee (JWLS)

- **Impedances** (CLVF, IMPE)
  - Absorbing boundary condition for fluid mesh (ABSO, INFI)
  - Loading boundary conditions (AIRB, PIMP)

European Commission

Materials (capabilities)

- **Structural**
  - Large displacements/strains/rotations
  - Plasticity
  - Hardening / Softening
  - Strain rate effect
  - Erosion
  - hyperelasticity

- **Fluid**
  - Perfect gas
  - Detonation
  - Gas mixture
  - Combustion

Materials: internal variables (ECRO)

DPDC

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent plastic strain
ECR(4) : Cube root of initial element volume (if version8)
ECR(5) : Lode angle
ECR(6) : Total variation of the isotropic hardening parameter
ECR(7) : Volumetric strain
ECR(8) : Plastic volumetric strain
ECR(9) : Ductile damage parameter
ECR(10): Brittle damage parameter
ECR(11): Ductile damage threshold
ECR(12): Brittle damage threshold
ECR(13): Current damage
ECR(14): Initial damage threshold in compression
ECR(15): Initial damage threshold in tension
ECR(16): filtered effective strain rate
ECR(17-22): Components of elastoplastic stress tensor
ECR(23-28): Components of viscoplastic stress tensor
ECR(29): Effective strain rate
ECR(30): Triaxiality
ECR(31): Static ductile damage threshold
ECR(32): Static brittle damage threshold

GAZP

ECR(1): pressure
ECR(2): density
ECR(3): velocity of sound
ECR(4): maximum pressure ever experienced
ECR(5): minimum pressure ever experienced
ECR(6): dynamic pressure: ($P_{\text{dyn}} = \frac{1}{2}\rho v^2$)
ECR(7): temperature (if c_V is not zero)
ECR(8): total specific energy ($E = h + \frac{1}{2}v^2$)

VPJC

ECR(1) : SIGMAH. Hydrostatic pressure ($\frac{1}{3}\sigma_{kk}$)
ECR(2) : PHI. Von Mises equivalent stress (σ_{eq})
ECR(3) : P. Equivalent plastic strain (p)
ECR(4) : PHITRIAL. Elastic trial equivalent (von Mises) stress
ECR(5) : F. Yield function (which should be close to 0.0)
ECR(6) : R. Total hardening of the material
ECR(7) : DDLAMBDA. Change of the incremental plastic multiplier (from one time step to another)
ECR(8) : DLAMBDA. Incremental plastic multiplier
ECR(9) : NRITER. Number of iterations to obtain convergence
ECR(10) : DLAMBDA / DT. Rate of plastic multiplier increment in time
ECR(11) : D. Damage (D), i.e. fraction of voids with respect to the gross cross-sectional area
ECR(12) : Failure indicator: 1.0 = Virgin Gauss Point, 0.0 = Failed Gauss Point
ECR(13) : T. Absolute temperature (T)
ECR(14) : WE. Cockcroft-Latham damage accumulation (W)
ECR(15) : Sound speed
ECR(16) : First principal stress (σ_1)
ECR(17) : Second principal stress (σ_2)
ECR(18) : Third principal stress (σ_3)

Elements

- Europlexus manual

3 SPATIAL DISCRETIZATION

```
EX03
ECHO
CONV WIN
KFIL
EROS 0.0
TRID ALE
DIME
  NALE 1
  NBLE 1
TERM
GEOM Q4GS PART 1
     CUVF hexa  PART 2
     PRVF penta PART 3
     BR3D bars  PART 4
     CL3D absor PART 5
TERM
```

Type of computation

Element definition

European Commission

Elements

NUMBER OF ELEMENTS TYPE	156

The code contains various formulations, including:

- Finite Elements, which may be used for both structural and fluid parts of the model;
- Spectral Elements, which can be used for the discretization of continuum-like solid parts which behave linearly (e.g. small-strain wave propagation);
- Finite Volumes, which are suited for the fluid parts;
- SPH particles, often used for high-speed impact problems;
- Diffuse Elements.

1D

CEA

num.	Name	Gibi	npt	dof	ngp	Remarks
22	TUBE	SEG2	2	1	1	fluid only (rigid tube)
23	TUYA	SEG2	2	7	2	tube coupled with FSI
24	CL1D	POI1	1	1	1	fluid boundary condition
25	BIFU	SUPE	1:9	7	1	bifurcation junction
26	CAVI	SUPE	1:9	1	1	cavity junction
31	CLTU	POI1	1	7	1	boundary condition with FSI
146	BREC	SEG2	2	7	1	pipeline rupture
147	TUVF	SEG2	2	1	1	rigid tube (1D vfcc)
148	TYVF	SEG2	2	7	1	tuvf coupled with FSI (1D vfcc)
149	BIVF	SEG2	2	1	1	bifurcation junction (1D vfcc)
150	CAVF	SEG2	1:9	1	1	cavity junction (1D vfcc)

Elements (2D)

CEA

num.	Name	Gibi	npt	dof	ngp	Remarks
1	COQU	SEG2	2	3	2	thin shell
2	TRIA	TRI3	3	2	1	triangle
3	BARR	SEG2	2	2	1	bar (membrane only)
4	PONC	POI1	1	2	1	circular bar(axisym.)
5	MEMB	SEG2	2	2	1	'virole' in membrane (axisym.)
7	CL2D	SEG2	2	2	1	boundary conditions
8	CAR1	QUA4	4	2	1	quadrangle with 1 Gauss pt.
9	CAR4	QUA4	4	2	4	quadrangle with 4 Gauss pt.
10	COQC	SEG2	2	3	1	thin shell with shear
15	FS2D	RAC2	4	2	1	F.S. coupling
28	PMAT	POI1	1	2	1	material point
45	TVL1	TRI3	3	2	1	Van Leer triangle
46	CVL1	QUA4	4	2	1	Van Leer quadrangle
114	BSHT	SEG2	2	2	-	bushing with translational dof
118	MAP2	—-	3	2	-	Point on solid edge
121	MAP5	—-	3	2	-	Point on 2D shell
124	INT4	—-	4	2	2	2D interface element
131	T3VF	TRI3	3	2	1	triangle finite volume
132	Q4VF	QUA4	4	2	1	quadrangle finite volume

JRC

num.	Name	Gibi	npt	dof	ngp	Remarks
38	Q92	QUA8	9	2	4	9-node quadrilateral
39	Q93	QUA8	9	2	9	9-node quadrilateral
42	CL23	SEG3	3	2	2	3-node b.c.s
43	ED01	SEG2	2	3	10	beam/conical-shell
49	Q92A	QUA8	9	2	4	Q92 on symmetry axis
52	FLU1	QUA4	4	2	1	fluid quadrilateral
54	PFEM	POI1	1	2	1	particle finite element
56	ED41	SEG2	4	3	10	old version of ED01
58	ADQ4	QUA4	4	2	1	advection-diffusion quadrilateral
64	FL23	TRI3	3	2	1	fluid triangle
65	FL24	QUA4	4	2	1	fluid quadrilateral
70	CL22	SEG2	2	2	2	2-node b.c.s
71	Q41	QUA4	4	2	1	ALE structural quadrilateral
72	Q42	QUA4	4	2	4	ALE structural quadrilateral
73	Q41N	QUA4	4	2	1	ALE structural quadrilateral
74	Q42N	QUA4	4	2	4	ALE structural quadrilateral
75	Q41L	QUA4	4	2	1	Lagr. structural quadrilateral
76	Q42L	QUA4	4	2	4	Lagr. structural quadrilateral
77	Q95	QUA8	9	2	4	test version of Q92
97	MC23	TRI3	3	2	1	finite volume fluid triangle
98	MC24	QUA4	4	2	1	finite volume fluid quadrilateral
100	Q42G	QUA4	4	2	4	ALE structural quadrilateral
105	MS24	QUA4	4	2	1	spectral "macro" quadrilateral
106	S24	QUA4	4	2	1	spectral "micro" quadrilateral
109	FUN2	SEG2	2	2	1	cable element
140	DEBR	POI1	1	2	-	debris particle

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Elements (3D)

CEA

num.	Name	Gibi	npt	dof	ngp	Remarks
6	CUBB	CUB8	8	3	8	brick based on B-bar method
11	CUBE	CUB8	8	3	1	brick with 1 Gauss pt
12	COQ3	TRI3	3	6	1	triangular thin shell
13	CUB6	CUB8	8	3	6	brick with 6 Gauss pt
14	COQ4	QUA4	4	6	4	quadrangular thin shell
16	FS3D	RAC3	8	3	1	F.S. connection (4-node face)
17	POUT	SEG2	2	6	2	beam
18	CL3D	QUA4	4	3	1	bound. cond. (4-node face)
19	BR3D	SEG2	2	3	1	spring or bar
20	PR6	PRI6	6	3	6	prism with 6 Gauss pt
21	TETR	TET4	4	3	1	tetrahedron with 1 Gauss pt
27	PRIS	PRI6	6	3	1	prism with 1 Gauss pt
28	PMAT	POI1	1	3	1	material point
29	CL3T	TRI3	3	3	1	bound. cond. (3-node face)
30	CUB8	CUB8	8	3	8	brick with 8 Gauss pt
32	APPU	POI1	1	6	1	support
33	MECA	SEG2	2	6	1	mechanism (articulated systems)
35	QPPS	QUA4	4	6	5	similar to Q4GR
41	TUBM	SUPE	1*	3*	1	connection 3D-1D
47	CMC3	TRI3	3	6	2	multilayer shell
48	FS3T	PRI6	6	3	1	F.S. connection (3-node face)
51	T3GS	TRI3	3	6	5	shell (Reissner-Mindlin)
79	BILL	POI1	1	3	1	particle element (NABOR and SPH)
80	ELDI	POI1	1	6	1	discrete element
81	CUVL	CUB8	8	3	1	Van Leer cube
82	PRVL	PRI6	6	3	1	Van Leer prism
83	DST3	TRI3	3	6	15	shell (Discrete Shear Triangle)
84	DKT3	TRI3	3	6	15	shell (Mindlin)
85	SHB8	CUB8	8	3	5	thick shell
89	SPHC	POI1	1	6	1	particle element (thick shell)
90	Q4G4	QUA4	4	6	4	shell (Batoz)
111	Q4GR	QUA4	4	6	5	idem Q4G4 (simplified : 1 pt)
112	Q4GS	QUA4	4	6	20	idem Q4G4 (simplified : 4 pts)
113	RL3D	SEG2	2	3	1	two-node spring
114	BSHT	—	2	3	–	bushing with translational dof
115	BSHR	—	2	6	–	bushing with trans. and rot. dof
116	TUYM	SUPE	1*	3*	1	connection 3D-1D
117	SH3D	—	3	6	–	node to shell connector
119	MAP3	—	4	3	–	point on a triangular facet
120	MAP4	—	5	3	–	point on a quadrangular facet

JRC

num.	Name	Gibi	npt	dof	ngp	Remarks
40	COQI	TRI3	3	6	15	triangular shell (small strain)
53	FLU3	CUB8	8	3	1	fluid brick
54	PFEM	POI1	1	3	1	particle finite element
57	ADC8	CUB8	8	3	1	advection-diffusion brick
62	CL32	QUA4	4	6	4	b.c.s for CQD4
63	CL33	QUA9	9	6	9	b.c.s for CQD9
66	FL34	TET4	4	3	1	fluid tetrahedron
67	FL35	PYR5	5	3	1	fluid pyramid
68	FL36	PRI6	6	3	1	fluid prism
69	FL38	CUB8	8	3	1	fluid hexahedron
78	CL3I	TRI3	3	3	1	3-node b.c.s
91	CQD4	QUA4	4	6	20	degenerated shell (Hughes-Liu)
92	CQD9	QUA9	9	6	45	degenerated shell (Hughes-Liu)
93	CQD3	TRI3	3	6	15	degenerated shell (Hughes-Liu)
94	CQD6	TRI6	6	6	20	degenerated shell (Hughes-Liu)
95	CLD3	TRI3	3	6	3	b.c.s for CQD3
96	CLD6	TRI6	6	6	4	b.c.s for CQD6
99	CL3Q	QUA4	4	3	1	4-node b.c.s
101	MC34	TET4	4	3	1	finite volume tetrahedron
102	MC35	PYR5	5	3	1	finite volume pyramid
103	MC36	PRI6	6	3	1	finite volume prism
104	MC38	CUB8	8	3	1	finite volume hexahedron
107	MS38	CUB8	8	3	1	spectral "macro" quadrilateral
108	S38	CUB8	8	3	1	spectral "micro" quadrilateral
110	FUN3	SEG2	2	3	1	cable element
140	DEBR	POI1	1	3	-	debris particle
144	C272	CU27	27	3	8	27-node cube
145	C273	CU27	27	3	27	27-node cube
151	CL92	QUA9	9	3	4	9-node (3D) b.c. for C272
152	CL93	QUA9	9	3	9	9-node (3D) b.c. for C273
155	C81L	CUB8	8	3	1	8-node cube
156	C82L	CUB8	8	3	8	8-node cube

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Elements (3D)

- **Structural**
  - Beam like elements (BR3D)
  - Shell elements (Q4GS, T3GS)
  - Solid elements (CUBE, CUB8, PRIS, TETR)
  - Material points (PMAT, DEBR)

- **Fluid**
  - Finite volumes (CUVF, PRVF, TEVF, PYVF)
  - Finite elements (FL38, FL36, FL34)

- **Boundary condition**
  - Shell elements (CL3D, CL3T)

Storage of results

- Europlexus manual

12 GROUP G—PRINTOUT AND STORAGE OF RESULTS

```
ECRI DEPL ECROU VITE TFRE 0.5E-3
          NOPO  NOEL
          ELEM LECT p1 TERM
     FICH ALICE TEMPS TFREQ 1.0e-4
                POINT lect p_capt term
                ELEM  lect p1 p2 p3 term
     FICH PVTK TFRE 0.1e-3!FREQ 0 TFRE 0.D0
               GROU AUTO
               VARI VCVI ECRO
```

Listing file

Alice temp file

Paraview file

European Commission

Storage of results

- **Nodal**
  - DEPL (displacement)
  - VITE (velocity)
  - ACCE (acceleration)
  - FEXT (external forces)
  - FLIA (link forces)

- **Elemental**
  - CONT (stress)
  - EPST (strain)
  - ECRO
  - RISK
  - FAIL
  - VCVI (fluid only)
  - ENER

Storage of results

- **Listing file (Ascii)**
  - Element/ node printouts with a defined output frequency
  - not very efficient
- **Alice file (binary)**
  - Europlexus storage type
  - Can be split
  - Is becoming very large but contains all the desired data
- **Alice temp file (binary)**
  - Europlexus storage type
  - Can be split
  - Very efficient but the user has to predefine the desired data
- **Paraview file (binary/ascii)**
  - Paraview storage type (pvtk)
  - Very efficient for visualizing purposes

Post-processing with EPX

15 GROUP ED—POST-TREATMENT BY EUROPLEXUS

```
CALC TINI 0.0 TFIN 200.E-3
SUIT
EXPL03AP
ECHO
RESU ALICE TEMPS GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
COUR 1 'Pressure' ECRO COMP 1 ELEM LECT e1 TERM
COUR 2 'Pressure' ECRO COMP 1 ELEM LECT e2 TERM
TRAC 1 2 AXES 1.0 'Pressure' YZER
     COLO bleu roug
     THIC 0.8 0.8
LIST 1 2 AXES 1.0 'Pressure' YZER
COUR 11 'VCVI' VCVI NORM ELEM LECT e1 TERM
COUR 12 'VCVI' VCVI NORM ELEM LECT e2 TERM
TRAC 11 12 AXES 1.0 'Velocity' YZER
     COLO bleu roug
     THIC 0.8 0.8
LIST 11 12 AXES 1.0 'Velocity' YZER
FIN
```

Read alice file

Create output curves

Print curves on a ps file

Print curves on a punch file

Post-processing with EPX - Curves

- **Curves**
- **Nodal / elemental quantities**
- **Zone quantities**
- **Curves as a function of space (SCOURBE)**
- **Read a curve (RCOURBE)**
- **Other special type of curves (PCOURBE, DCOURBE etc.)**
- **Curves manipulation**
  - Integration
  - Summation
  - Max, mean, min
- **Postscript file creation (TRACE)**
  - Axis definition
  - Color, thickness etc.
  - Max, mean, min
- **Punch file creation (LIST)**

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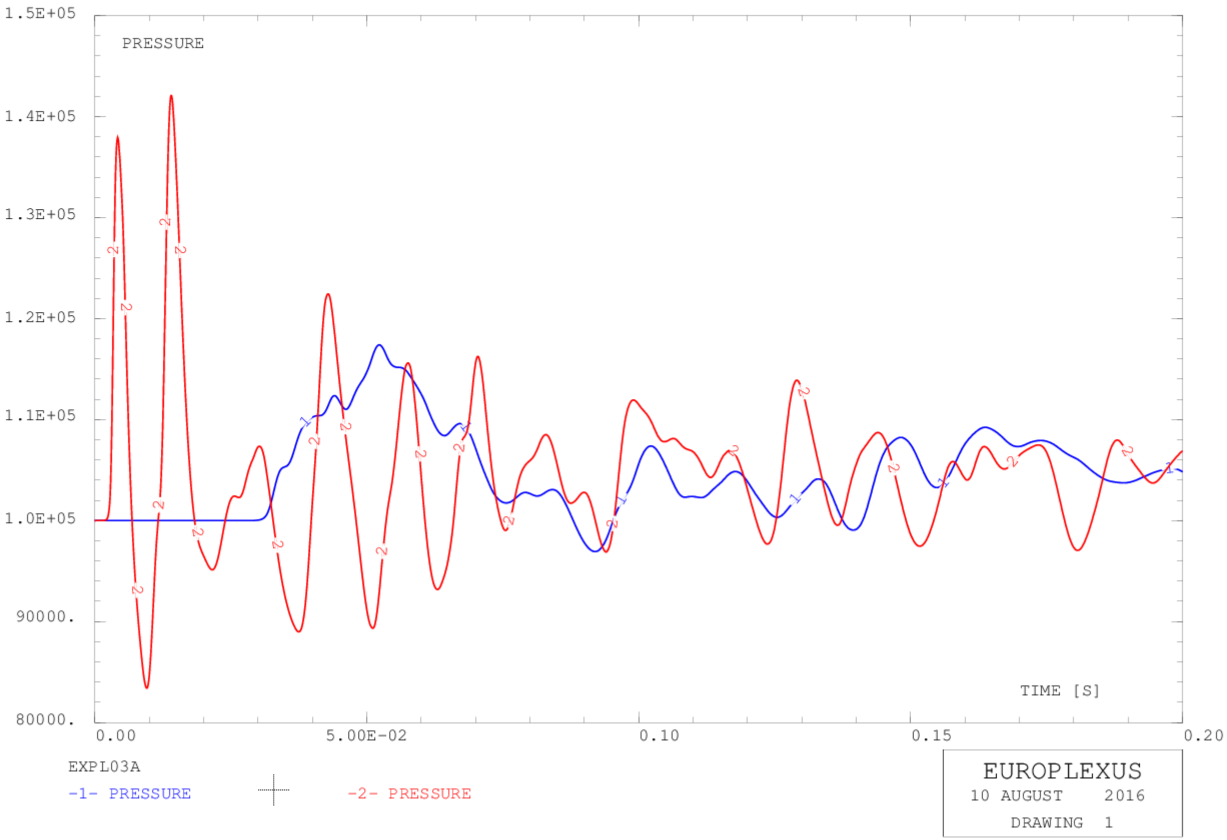
Post-processing with EPX

Post-script file example



Punch file example

```
VALUES    11        COMPONENTS 1
*      Time [s]             Pressure1
*      T                    Pressure
       0.000000E+00         1.000000E+05
       1.201111E-04         1.000000E+05
       2.161999E-04         1.000000E+05
       3.122888E-04         1.000000E+05
       4.083777E-04         1.000000E+05
       5.044665E-04         1.000000E+05
       6.005554E-04         1.000000E+05
       7.206665E-04         1.000000E+05
       8.167553E-04         1.000000E+05
       9.128442E-04         1.000000E+05
       1.008933E-03         1.000000E+05
VALUES    11        COMPONENTS 1
*      Time [s]             Pressure2
*      T                    Pressure
       0.000000E+00         1.000000E+05
       1.201111E-04         1.000000E+05
       2.161999E-04         1.000000E+05
       3.122888E-04         1.000000E+05
       4.083777E-04         1.000000E+05
       5.044665E-04         1.000000E+05
       6.005554E-04         1.000000E+05
       7.206665E-04         1.000000E+05
       8.167553E-04         1.000000E+05
       9.128442E-04         1.000000E+05
VALUES    11        COMPONENTS 1
*      Time [s]             Velocity
*      T                    VCVI
       0.000000E+00         0.000000E+00
       1.201111E-04         0.000000E+00
       2.161999E-04         0.000000E+00
       3.122888E-04         0.000000E+00
       4.083777E-04         0.000000E+00
       5.044665E-04         0.000000E+00
       6.005554E-04         0.000000E+00
       7.206665E-04         0.000000E+00
       8.167553E-04         0.000000E+00
       9.128442E-04         0.000000E+00
       1.008933E-03         0.000000E+00
```

Post-processing with EPX

- **REGIONS (11.9)**
  - Group of Nodes or Elements
  - Monitor the quantities of a group
  - Energy balance or average values
  - Listing, punch , alice files
  - Be aware of the available quantities
  - The group has to be defined in advance
  - Zones solution

```
"REGION"  ( 'nom region'
    $[ "RMAS" ; "VOLU" ; "BARY" ; "DIMX" ; "DIMN" ;
       "DMOY" ; "VEMX" ; "VEMN" ; "VMOY" ; "ACMX" ;
       "ACMN" ; "AMOY" ; "IMPU" ; "ECIN" ; "WINT" ;
       "WEXT" ; "PDV"  ; "WINJ" ; "RESU" ; "IRES" ;
       "ECRG" ; "ECRM" ; "EMAS" ; "FLIR" ; "RISK" ;
       "EROD" ; "ENDO" ; "CLAS' ; "EPSM" ; "TOUT" ]$
     < "DIRX" rx "DIRY" ry "DIRZ" rz >
    |[     /LECTURE/     ;
       "POIN" /LECTURE/  ]| )
```

```
REGION : PLATE
------------
                         INTERNAL ENERGY (WINT)         =  3.01728E+03
                         TRAVAIL DES PRESSIONS (PDV)    = -1.72803E+01
                         INTRODUCED ENERGIE             =  0.00000E+00
                         KINETIC ENERGIE (ECIN)         =  4.34258E+02
                         KINETIC ENERGIE (COMP.)        =  4.94800E-03  9.31900E-03  4.34243E+02
                         MASS       (COMPOSANTES)       =  1.78668E+01  1.78668E+01  1.78668E+01
                         MASS    (SUM OF ELEMENTS)      =  1.78668E+01
                         DISPLAC. MAXIMUM  (COMP.)      =  7.15988E-04  7.35179E-04  1.28955E-01  1.28955E-01
                         DISPLAC. MINIMUM  (COMP.)      =  1.70512E-09  2.75385E-09  5.91600E-02  5.91612E-02
                         DISPLAC. AVERAGE (COMP.)       = -6.43949E-08 -2.62663E-06  1.04001E-01
                         VELOCITY MAXIMUM  (COMP.)      =  1.12027E-01  1.07962E-01  9.73004E+00  9.73028E+00
                         VELOCITY MINIMUM  (COMP.)      =  1.79196E-06  1.14166E-06  4.70004E+00  4.70010E+00
                         VELOCITY AVERAGE (COMP.)       =  6.47717E-06 -9.60583E-04  6.83815E+00
                         ACCELER. MAXIMUM  (COMP.)      =  3.23449E+02  6.26475E+02  3.88293E+03  3.88312E+03
                         ACCELER. MINIMUM  (COMP.)      =  2.58365E-03  4.61048E-03  1.78445E-02  4.96671E+00
                         ACCELER. AVERAGE (COMP.)       =  1.64996E+01  3.29587E+01  2.24849E+02
                         IMPULSION   (COMPOSANTES)      =  1.15726E-04 -1.71625E-02  1.22176E+02
                         BARYCENTRE  (COMPOSANTES)      =  1.25000E-01  1.44997E-01  9.90006E-02
                         VOLUME                         =  6.38204E-03
                         ENERGIE MECANIQUE (WEXT)       =  0.00000E+00
                         SUM (FEXT.DT)   (COMPOS.)      =  0.00000E+00  0.00000E+00  0.00000E+00
                         RESULTANTE  (COMPOSANTES)      =  0.00000E+00  0.00000E+00  0.00000E+00
                         SOMME(REGION) ECR (COMP.)      = -3.72750E+08  6.38530E+11  7.21494E+00  0.00000E+00  4.11774E+04
                                                           0.00000E+00  5.50080E+12  0.00000E+00  0.00000E+00  0.00000E+00
                         R.F.LIAI/LINK (COMPOSANTES)    =  0.00000E+00  0.00000E+00  0.00000E+00
                         NBRE ELTS CASSES               =            0
                         NBRE ELTS PARTIELLEMENT CASSES =            0
                         ELTS REGION /= ELTS CLASSES :AUCUNE IMPRESSION RELATIVE AUX CLASSES
                         TOTAL RISK (EARDRUM)           =  0.00000E+00
                         TOTAL RISK (DEATH)             =  0.00000E+00
                         EPST (COMP.)                   =  7.15564E-05  1.57330E-04 -2.28067E-04  1.04649E-07  4.40190E-07
                                                           5.68338E-08  0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
                                                           0.00000E+00  0.00000E+00
```

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Interactive commands with EPX

- EPX manual
- CONV WIN (only for windows)

15 GROUP O—INTERACTIVE COMMANDS

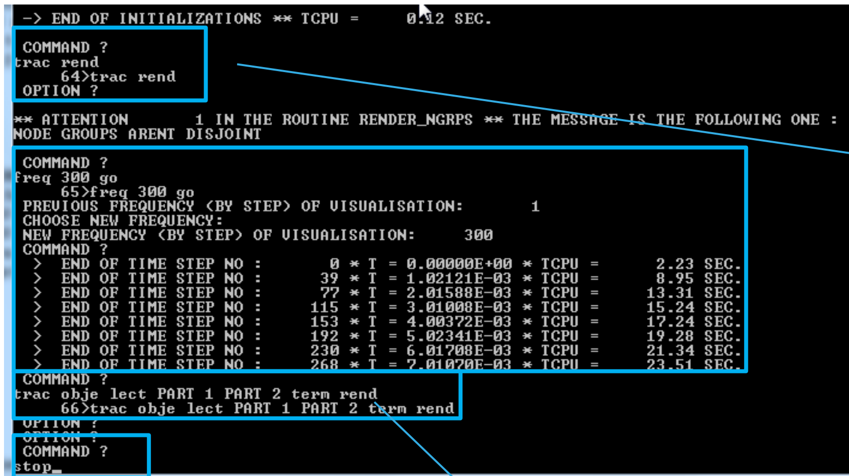
```
IMPA01
ECHO
CONV WIN
KFIL
```

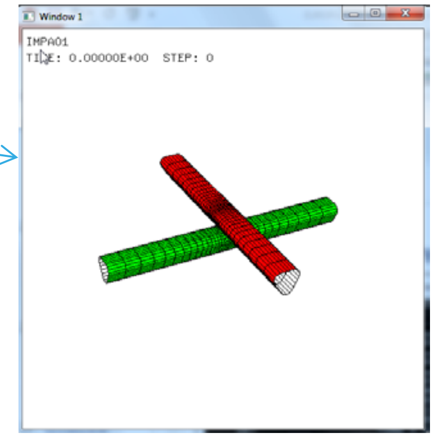
1

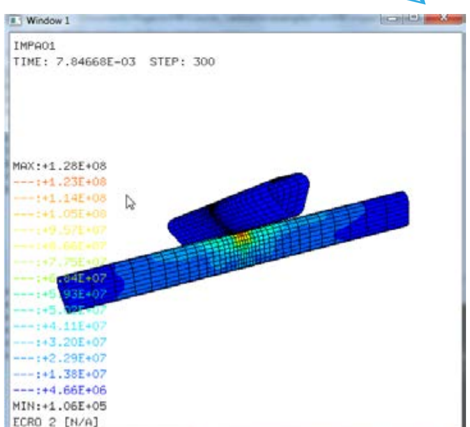
2

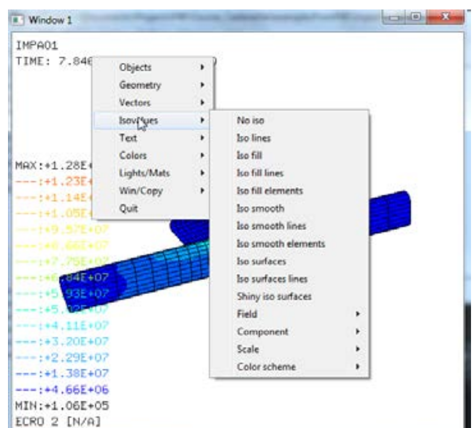
3

4









Interactive commands with EPX

15 GROUP O—INTERACTIVE COMMANDS

- “TRAC REND” or “TRAC OBJE LECT ... TERM REND”
- “FREQ ..” or “TFREQ ..”
- “TIME”
- “INFO”
- “HPIN”, “NOHP”
- “GO”
- “STOP”

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Boundary conditions

8 GROUP D—LINKS

Finding the Lagrange Multipliers (2)

- The CD scheme for the velocity and constant Δt is:
  $\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \Delta t \cdot \underline{a}^{n+1}$
- Substituting this into the constraint $\underline{\underline{C}}\,\underline{v} = \underline{b}$ gives:
  $\underline{\underline{C}}\,\underline{v}^{n+3/2} = \underline{\underline{C}}\,\underline{v}^{n+1/2} + \Delta t \cdot \underline{\underline{C}}\,\underline{a}^{n+1} = \underline{b}$
- From this we obtain:
  $\underline{\underline{C}}\,\underline{a} = \frac{1}{\Delta t}(\underline{b} - \underline{\underline{C}}\,\underline{v}^{n+1/2}) = \frac{1}{\bar{\gamma}}(\underline{b} - \underline{\underline{C}}\,\underline{v}^{n+1/2})$ having posed: $\boxed{\bar{\gamma} = \Delta t}$
- For a variable Δt in time, one has simply:
  $\boxed{\bar{\gamma} = \frac{\Delta t^n + \Delta t^{n+1}}{2}}$

43

- **Coupled Lagrange multipliers (implicit)**
  - Cholesky
  - Iterative solvers (Pardiso etc)
  - BLOQ, FLSR, PINBALLS, CONT SPLA

```
LINK COUP SPLT NONE
          SOLV PARDISO
          BLOQ 123 LECT fix3 TERM
  Armat   beton lecture wal TERM
          ferr lecture  bars term
     PINB BODY LECT FOA TERM
          BODY LECT WALC TERM
          BODY LECT WALF1 WALF2 TERM
     CONT SPLA NX 0 NY 1 NZ 0 LECT symy TERM
     CONT SPLA NX 0 NY 0 NZ 1 LECT symz TERM
```

- **Decoupled (explicit)**
  - Imposed via ad-hoc direct methods
  - BLOQ, FLSW, PINBALLS (penalty method)

```
LINK DECO
     PINB PENA SFAC 1.0
          BODY FROT MUST 0.15 MUDY 0.1 GAMM 0 !MLEV 5
                                              DMIN 0.0008
          LECT lframeb TERM
          BODY FROT MUST 0.15 MUDY 0.1 GAMM 0 !MLEV 5
                                              DMIN 0.0008
          LECT uframe TERM
     FLSW STRU LECT scoup TERM
          FLUI LECT fcoup TERM
          R 0.0088    ! 0.87*H_FLUID = 0.87*0.01 = 0.0087
          HGRI 0.0052 ! Slightly bigger than the fully refined
                      ! fluid element (for this case)
                      ! h_f^ref = h_f^base / 2^(lmax-1) =
                      ! 0.01 / 2^1 = 0.005
```

Boundary conditions

- Blockages (8.5)
- Time-limited blockages (8.6)
- Symmetry conditions (8.8.6)
- Sliding (8.27, 8.48)

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Fluid boundary conditions

- **Absorbing boundaries**
  - IMPE ABSO (FE)
  - CLVF ABSO, INFI (VFCC)
  - Applied via appropriate (CL) elements

- **Reflecting boundaries**
  - Every free face in 3D or edge in 2D (for FV)
  - FSR for FE

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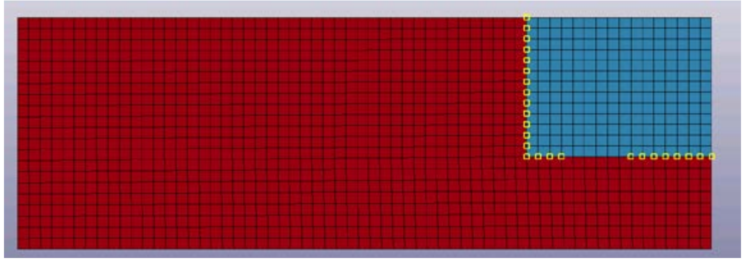
Slides\videos\GFM1.avi
Slides\videos\full21b2avi_01.avi



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Loading conditions

- **Loads**
  - Gravity
  - Rotational
  - Factorized

10 GROUP F—LOADS

```
CHAR CONS GRAV 0.0 0.0 -9.81
     LECT _DEBR TERM ! gravity acts only on debris particles
```

- **Impedances (7.8)**
  - Load via CL elements
  - Imposed pressure (PIMP)
  - Blast load (AIRB)

```
IMPE PIMP RO 7850.0 PRES 43.1e6 PREF 1.0E5
     LECT presur TERM
IMPE PIMP RO 7850 PRES 1.0 PREF 1.0E5 FONC 1
     LECT preplat TERM
IMPE AIRB X 0.0 Y 0.0 Z -0.625
     MASS 0.0402 TAUT
     LECT pblast TERM
```

- **Initial conditions**
  - Initial velocity, stress (INIT)
  - Harmonic function

9 GROUP E—FUNCTIONS AND INITIAL CONDITIONS

```
INIT VITE 3  -12.0 LECT MES FOA MAS TERM
```

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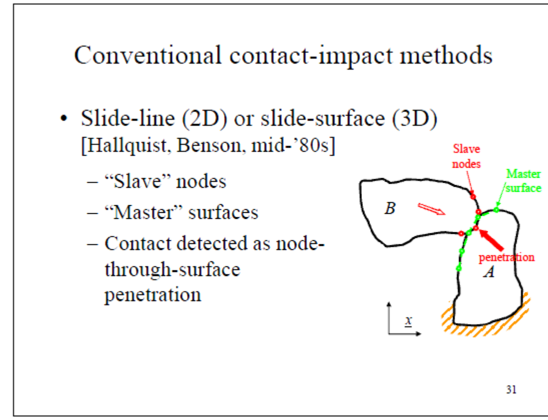
Contact models

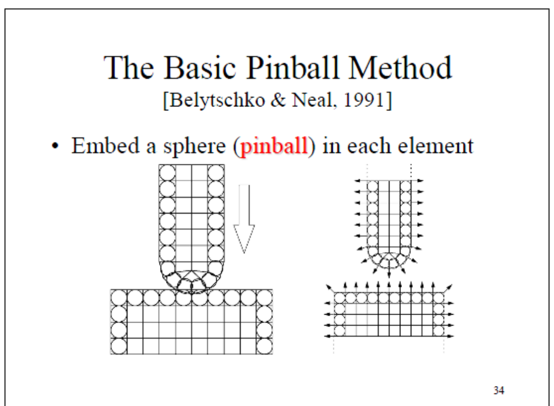
- **Sliding surfaces “GLIS” (8.27)**
  - coup, deco
  - Less robust

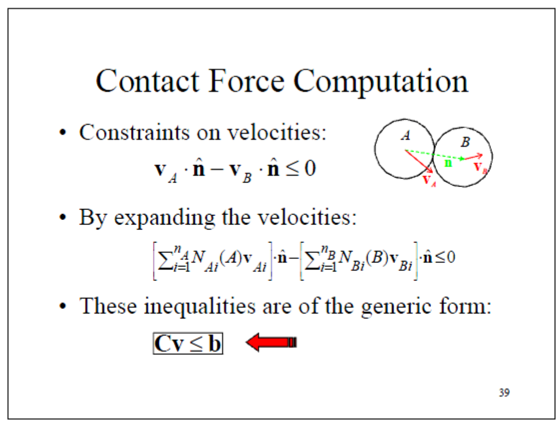
```
GLIS 2 FROT MUST 0.15 MUDY 0.1 GAMM 0 ! Contact surface #1
       PGAP 0.4E-3
       MAIT LECT lframe TERM
       PESC LECT plateN  TERM
       FROT MUST 0.15 MUDY 0.1 GAMM 0 ! Contact surface #2
       PGAP 0.4E-3
       MAIT LECT uframeb TERM
       PESC LECT plateN   TERM
```

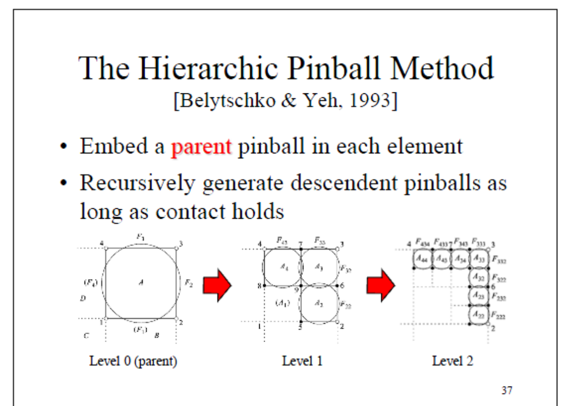


- **Pinball model “PINB” (8.48)**
  - coup, deco
  - More robust for impact problems
  - Efficient for complicated geometries

```
PINB BODY LECT FOA TERM
     BODY LECT WALC TERM
     BODY LECT WALF1 WALF2 TERM
     BODY LECT SUPF TERM
     EXCL PAIR 1 3
     EXCL PAIR 1 4
     EXCL PAIR 2 3
     EXCL PAIR 2 4
```







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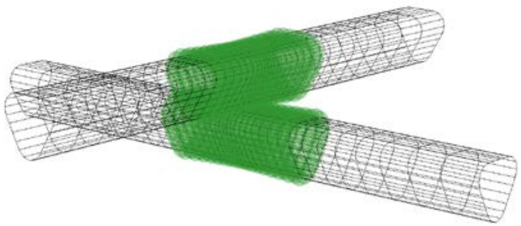
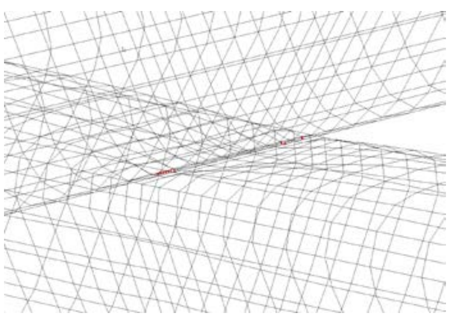
Pinball model

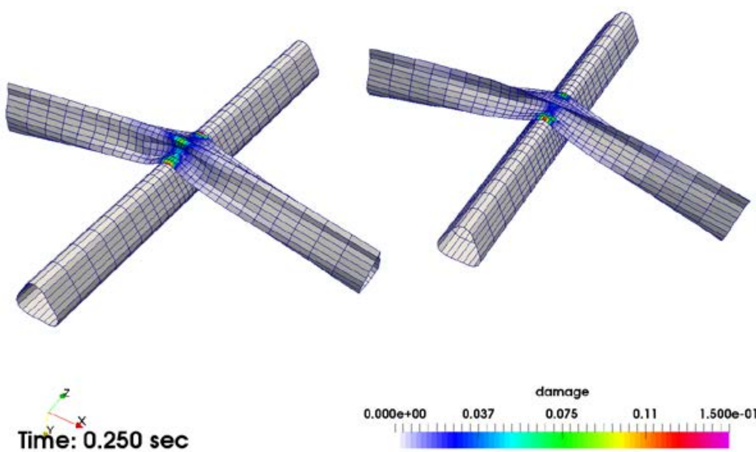
- **Drop analysis**
  - 2 bodies (beams)
  - One fixed the other with uniform velocity
  - Same material different thickness



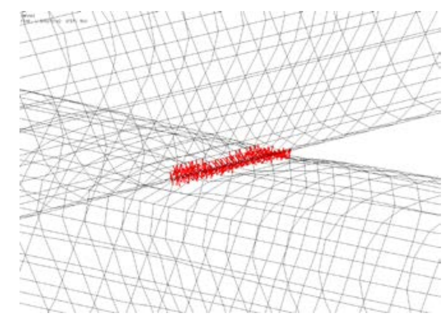
- **Pinball parameters**
  - Hierarchy level for descendants (MLEV)
  - Self-contact (SELF)
  - Exclude pairs (EXCL)

MLEV 0





MLEV 2



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Pinball model

- **Drop analysis**
  - Linear – Linear, uniform velocity   Slides\videos\An1.avi

```
MATE LINE RO 7800 YOUN 2.E11 NU 0.3
          LECT PART 1 PART 2 TERM
```

```
LINK COUP SPLT NONE SOLV PARD
     BLOQ 123 LECT fix1 fix2 TERM
     PINB BODY LECT bod1 TERM
          BODY LECT bod2 TERM
INIT VITE 2 30 LECT PART 2 TERM
```

  - Plastic – Linear , uniform velocity (5 times slower)   Slides\videos\An2.avi

```
MATE LINE RO 7800 YOUN 2.E11 NU 0.3
          LECT PART 1 TERM
     VPJC RO 7850.0 YOUN 2.1E11 NU 0.33 ELAS 3.257E8 mxit 500
          QR1 2.348E8 CR1 56.2 QR2 4.457E8 CR2 4.7
          PDOT 5.E-4 C 1.E-2 TQ 0.9 CP 452.0
          TM 1800.0 M 1.0 DC 1.0 WC 555.0E6
          LECT PART 2 TERM
```

  - Plastic – Plastic, rotational velocity   Slides\videos\An5.avi

```
LINK COUP SPLT NONE SOLV PARD
     BLOQ 123 LECT fix1 fix2 TERM
     BLOQ 123 LECT fix3 TERM
     PINB BODY LECT bod1 TERM
          BODY LECT bod2 TERM
CHAR CONS GRAV 0 9.80665 0 LECT tous TERM
INIT ROTA ORIG -20 1.0 -0.5764
          VECT 0 0 1
          OMEG 1.2
     LECT PART 2 TERM
```

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Impedances

Superposed elements (CL3D, CL3T)

- Shell: pressure
- Fluids: Absorbing boundaries

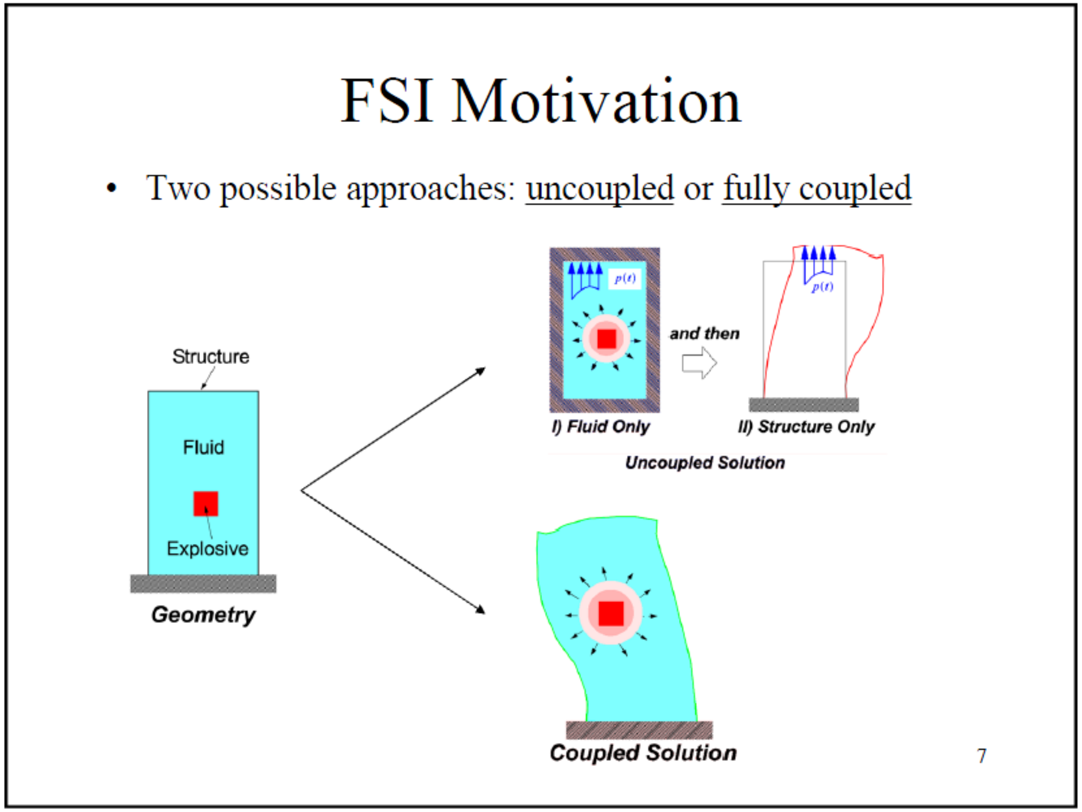
Material IMPE for loading

IMPE AIRB NODE LECT charge TERM MASS 1
LECT impe TERM

Fluid-Structure Interaction (FSI)

Fluid-structure interaction motivation

- **Fluid behavior**
  - Reflections
  - Channeling effect
  - Shadowing effect



- **Structural behavior**
  - Significant deformation
  - Failure and element erosion
  - Formation of flying debris

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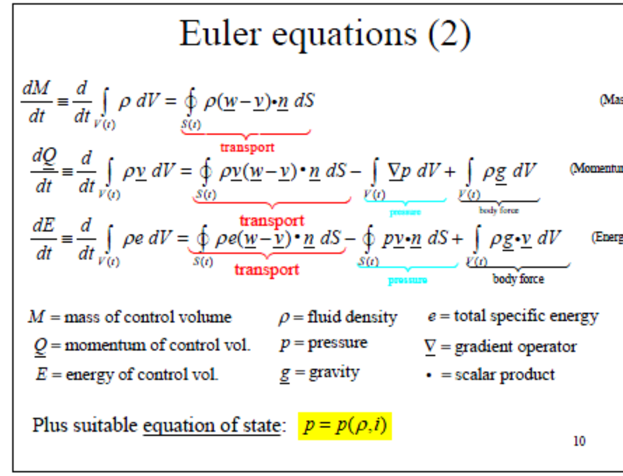
Fluid-structure interaction

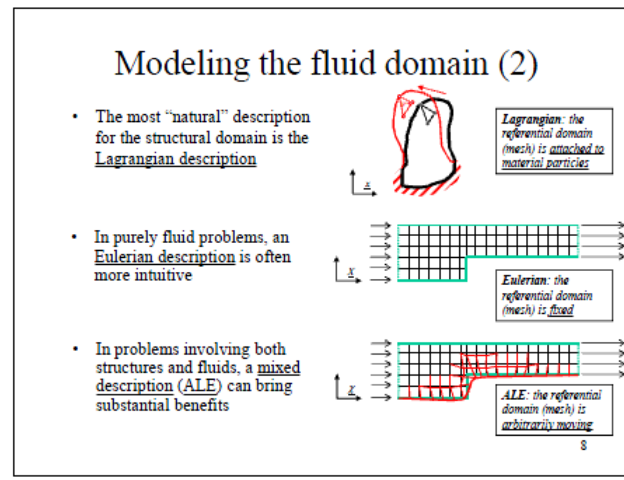
- **Fluid domain**
  - Eulerian
  - Compressible and inviscid
  - Discretization: FE, NCFV, FVCC

- **Structural domain**
  - Lagrangian
  - Discretization: FE

- **FSI enforcement**
  - Strong, constrains on the velocities (implicit)
  - Weak, pressures force/ fluxes (explicit)

- **FSI discretization**
  - Conforming mesh
  - Non-conforming mesh (embedded)





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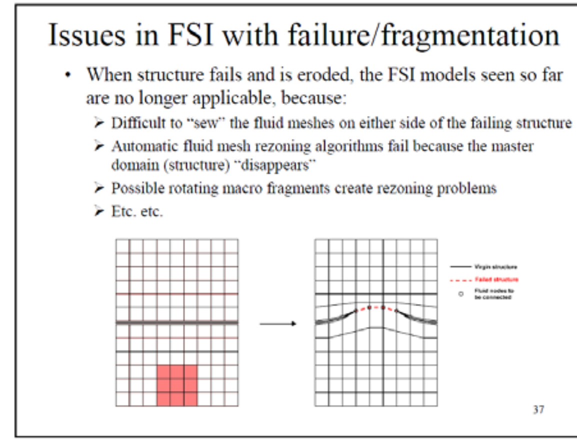
FSI discretization



- **Conforming mesh**
  - Medium computational cost +
  - Robust +
  - Rezoning problems –
  - No structural failure –
  - High complexity in the preparation of the mesh –

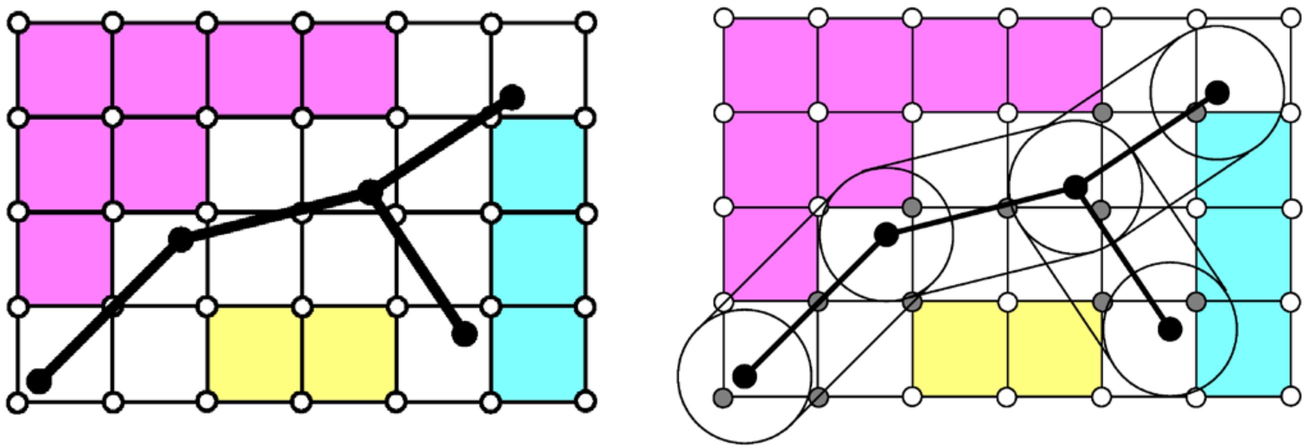
- **Non-conforming mesh**
  - Treats cases with significant deformation (failure etc.) +
  - Low complexity in the preparation of the mesh +
  - Robust +
  - High computational cost –
  - Sensitive to the parameters of the influence domain –

FSI embedded model

- **Automatically build up an "influence domain" around the structure (a sphere at each S node)**

- **Identify (fast search) fluid nodes F currently located within the influence domain**

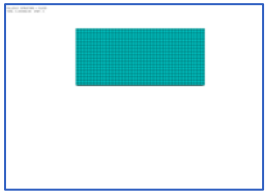
- **Impose suitable constraints on velocities : $v_F \cdot n_{S*} - v_{S*} \cdot n_{S*} = 0$ (n_{S*} is the normal to the structure, S* is closest structural point to fluid node)**



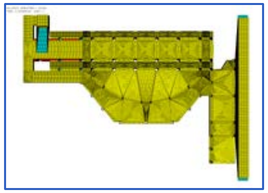
The grayed fluid nodes are coupled with the structure

FSI embedded model

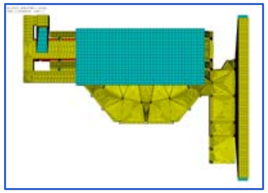
- **Fluid mesh regular parallelepiped grid**



- **Structural mesh**

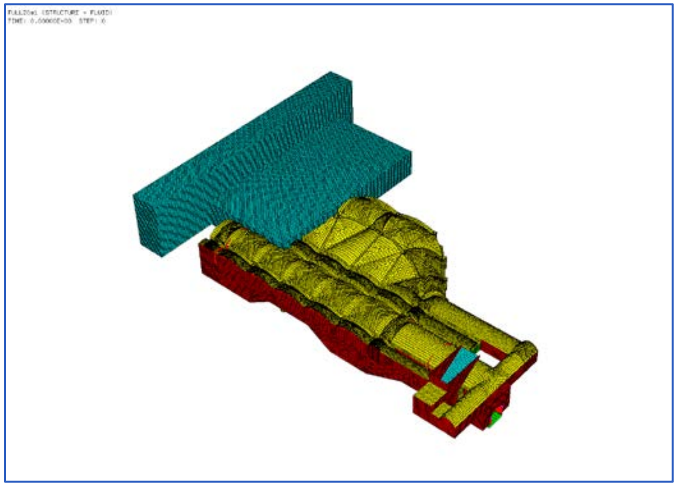


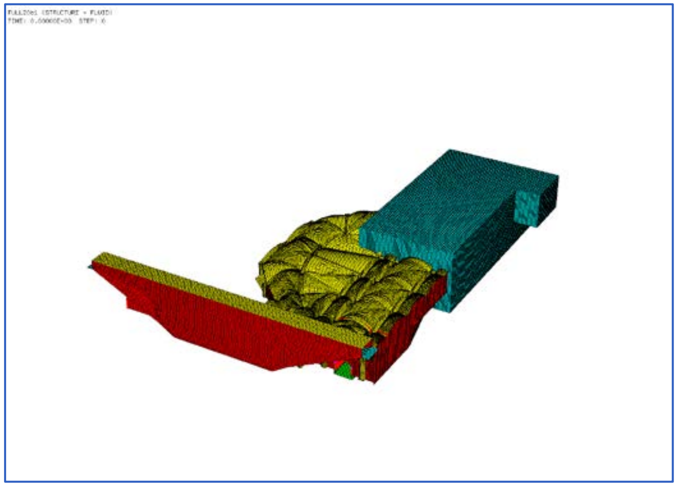
- **The two meshes are simply superposed**

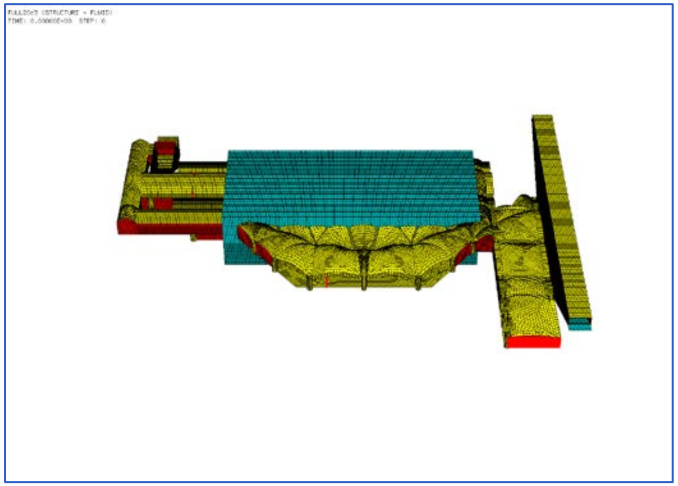


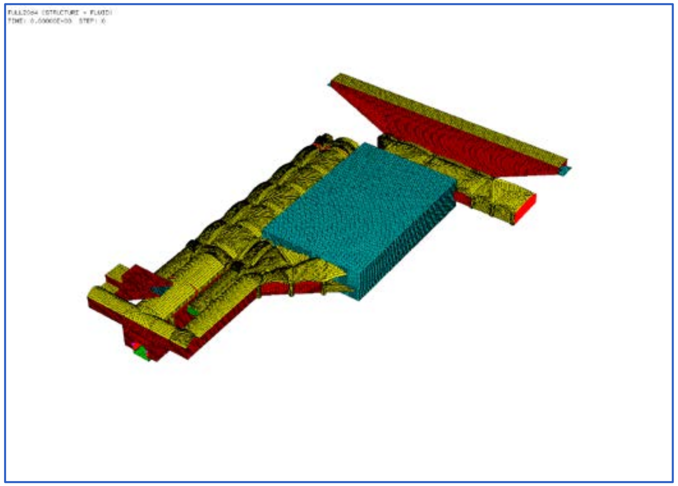
- **Absorbing boundaries on the envelope of the fluid mesh**

FSI embedded model









Fluid boundary conditions

- **Absorbing boundaries**
  - IMPE ABSO (FE)
  - CLVF ABSO, INFI (VFCC)
  - Applied via appropriate (CL) elements

- **Reflecting boundaries**
  - Every free face in 3D or edge in 2D (for FV)
  - FSR for FE

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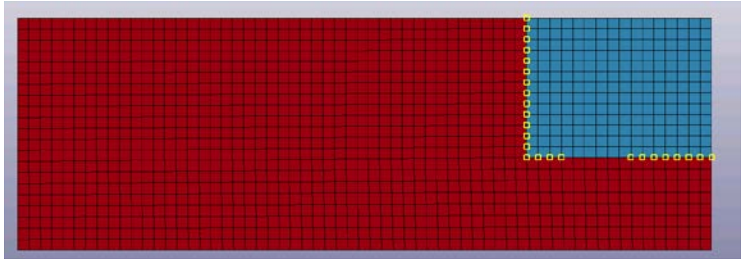
Slides\videos\GFM1.avi
Slides\videos\full21b2avi_01.avi



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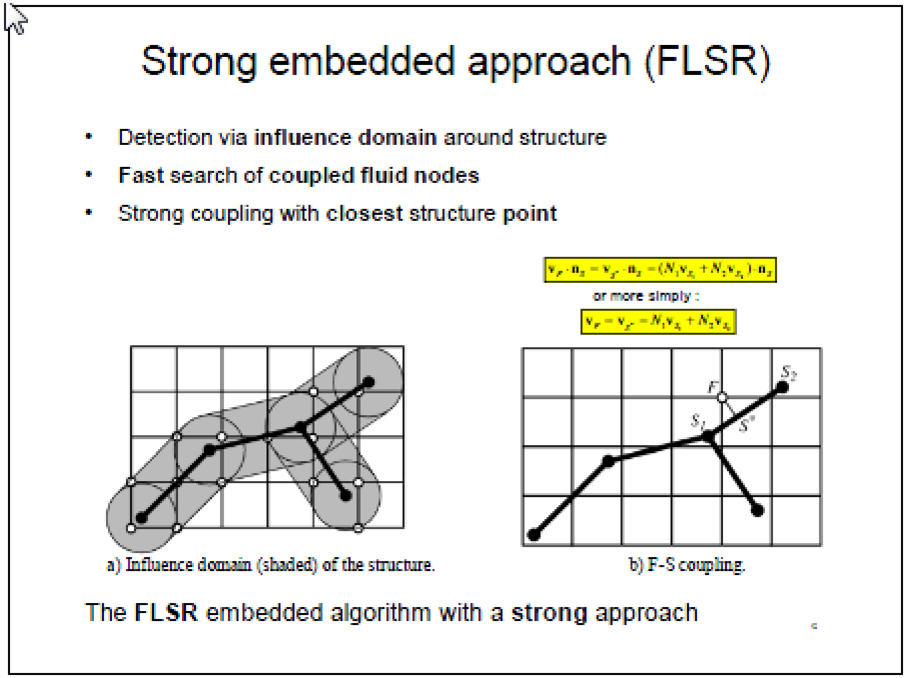
FSI Approaches (embedded)

- **General**
  - FE for the fluid mesh –
  - Coupled –
  - Robust +

- **Input**
  - Finite El. 2D: FL24, FLUT
  - Finite El. 3D: FL38, FLUT
  - Abs. Bound. 3D: CL3Q, IMPE ABSI



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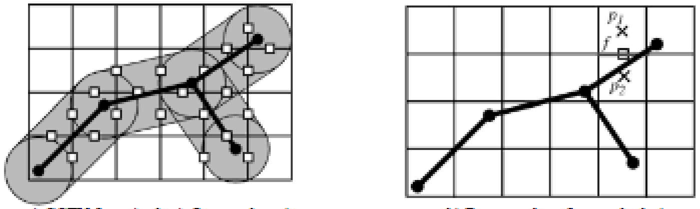
FSI Approaches (embedded)

- **General**
  - FV for the fluid mesh +
  - Decoupled +
  - Robust +

Weak embedded approach (FLSW)

- Detection via **influence domain** around structure (= FLSR)
- **Fast search of coupled fluid faces (for CCFV)**
- Weak coupling : pressure force to **closest structure point**
- Necessary to **block numerical fluxes** (= NCFV)



a) CCFV faces in the influence domain. b) Pressure drop force calculation.

The **FLSW** embedded algorithm with a **weak** approach

- **Inputs**
  - Finite Vol 1D: TUVF, GAZP
  - Finite Vol 2D: Q4VF, GAZP
  - Finite Vol 3D: CUVF, GAZP
  - Abs. Bound. 3D: CL3D, CLVF

FSI embedded parameters

- **Structural influence domain**
  - The contained fluid entities (centroids, interfaces) will be coupled
  - Related to the size of the fluid mesh
  - Too thin missing interfaces – leakages
  - R: radius of influence sphere

Prescribed (fixed) radius R of influence spheres at each coupled structural node. In the special, but frequent, case of a uniform structured fluid mesh (uniform square or cube elements) it is suggested to take R slightly larger than the semi-diagonal of a fluid element. This means that, for a 2D uniform square fluid mesh of side L_Φ one should take $R = 0.71L_\Phi$ while for a 3D uniform cube fluid mesh of side L_Φ one should take $R = 0.87L_\Phi$.

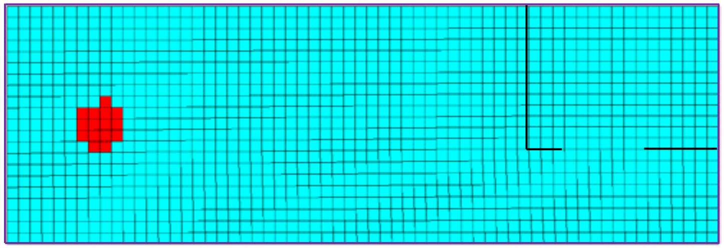
- **Fast search of coupled fluid entities**
  - Speed up the calculation
  - Essential for large models
  - Minimum size + accuracy of results
  - HGRI: $h_g = 1.01 \max(h_F, h_S)$

h_F = size of the fluid mesh

h_S = size of the structural mesh

FSI Inputs

- **Fluid only**

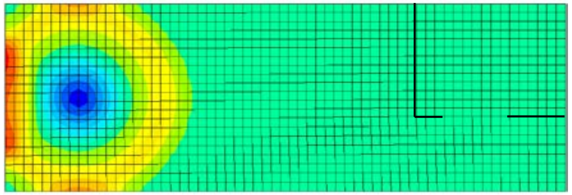


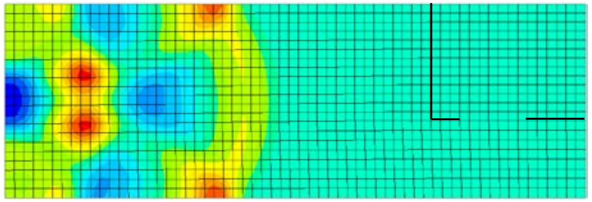
- **High pressure zone**
- **Ambient pressure zone**
- **Duplicated nodes (reflecting boundaries)**
- **Free edges (reflecting boundaries)**

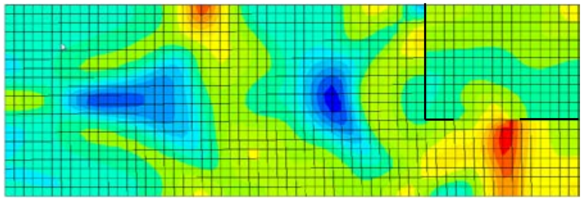
```
ECHO
KFIL
DPLA EULE
GEOM Q4VF PART 1 PART 2 TERM

 MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75
             PINI 0.5E6 PREF 1.E5
             LECT expl TERM
      GAZP RO 1.1897 GAMMA 1.4 CV 716.75
             PINI 1.E5 PREF 1.E5
             LECT air TERM

 OPTI NOTE LOG 1
      CSTA 0.5
      VFCC FCON 6 ! Solveur HLLC
      ORDR 2 ! Ordre 2 en espace
      OTPS 2 ! Ordre 2 en temps
      RECO 1 ! Reconstruction de type Green-Gauss
      LMAS 3 ! k-limiteur de Dubois (eq. masse)
      LQDM 3 ! k-limiteur de Dubois (eq. QDM)
      LENE 3 ! k-limiteur de Dubois (eq. energie)
      KMAS 0.75 ! Coefficient de limitation (eq. masse)
      KQDM 0.75 ! Coefficient de limitation (eq. QDM)
      KENE 0.75 ! Coefficient de limitation (eq. energie)
      CENE ! Correction de l'energie interne
 CALC TINI 0.0 TFIN 200.E-3
```







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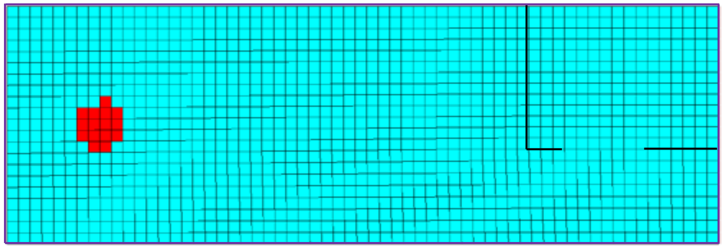
FSI Inputs

- **Fluid + structure (conforming mesh)**

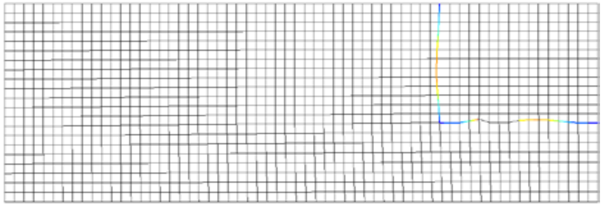


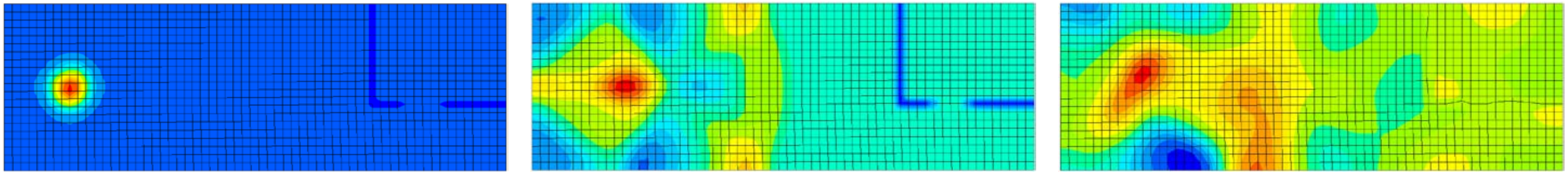
- **High pressure zone**
- **Ambient pressure zone**
- **Structural elements (deformable)**
- **Free edges (reflecting boundaries)**

```
ECHO
KFIL
DPLA ALE
DIME NALE 1 NBLE 1 TERM
GEOM Q4VF PART 1 PART 2 ED01 PART 3 PART 4 TERM

 GRIL LAGR LECT NSET 5 TERM
      EULE LECT NSET 6 TERM
      AUTO AUTR

 MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75
           PINI 0.5E6 PREF 1.E5
           LECT expl TERM
      GAZP RO 1.1897 GAMMA 1.4 CV 716.75
           PINI 1.E5 PREF 1.E5
           LECT air TERM
      VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
           TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
           LECT stru TERM
 LINK COUP BLOQ 123 LECT NSET 7 TERM
```





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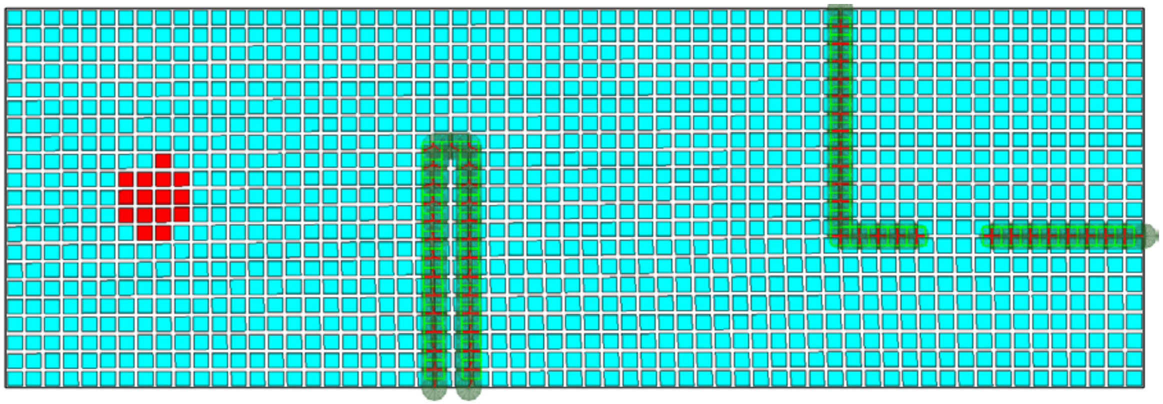
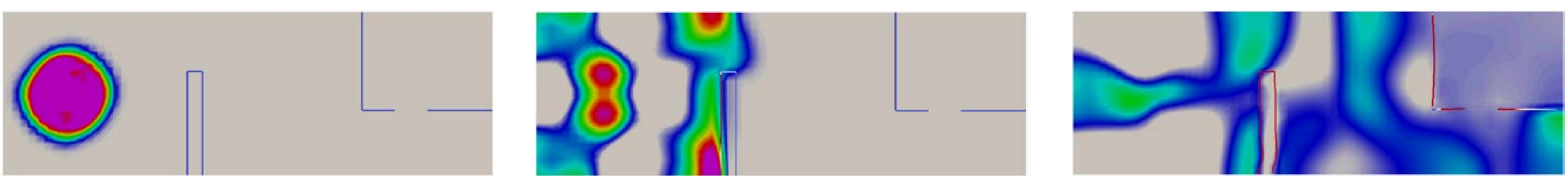
FSI Inputs

- **Fluid + structure (embedded)**



```
LINK COUP BLOQ 123 LECT NSET 9 TERM
LINK DECO FLSW STRU LECT stru TERM
          FLUI LECT flui TERM
          R 0.17
          HGRI 0.24
          DGRI
          FACE
          BFLU 2 FSCP 1
```

- **FSI coupling**
- **Blocked fluxes**



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FSI conclusions

Model	Calculation time	Positive	Negative
EULER	8	Low calculation cost	No structure
FSA	51	Medium calculation cost Accurate	Rezoning No structural failure High preparation cost
FLSW	152	Medium preparation cost Accurate Significant deformations Structural failure	High calculation cost Sensitive to influence domain parameters

- **What approach should I select?**
  - **The nature of the problem**
  - **Which phenomena should be considered**

fast transient dynamics • fluid-structure interaction • multiphysics

Failure / Erosion / Debris

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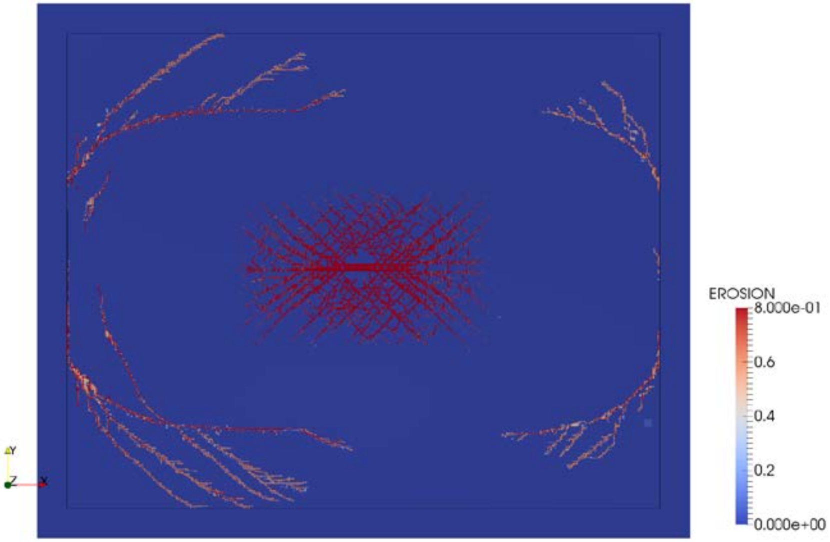
Failure / erosion

- Failure: reaching a certain criteria in an IP
- Erosion: removing an element from the calculation

Failure: material behaviour:

- Damage
- Plastic strain
- Pressure
- ...



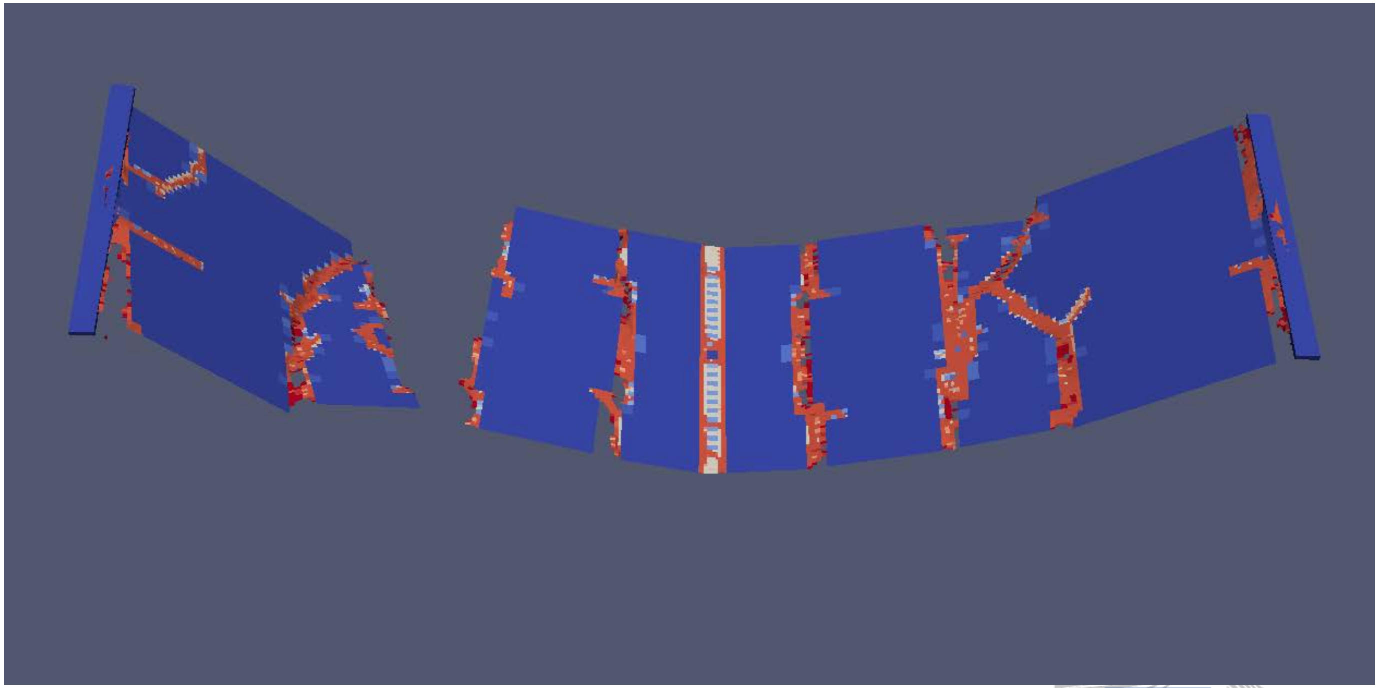
Failure (VM23)

```
"VM23"  "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige ...
          <"FAIL" $[ VMIS ; PEPS ; PRES ; PEPR ]$ "LIMI" limit>
          "TRAC" npts*(sig eps)
          /LECTURE/
```

VMIS Von Mises stress (isotropic criterion)
PEPS for a criterion based upon the principal strain
PRES for a criterion based upon the hydrostatic stress
PEPR for a criterion based upon the principal strain if the hydrostatic stress is positive (traction):
if the hydrostatic stress is negative (compression) there is no failure.

Erosion

- Material has reached a failure mode (damage or other criteria)
- element distorted (cannot be treated any more) (CROI)
- time step size is too small (CALC TFAI)
- Parts of the model should be removed at a certain time step or due to further criteria (displacement erosion, fantome elements)
- Erosion of attached element (CLxx)



Erosion

- EROS Idam CROI

Idam: ratio of failed IP to total IP from which on the element is eroded

- Options in the material law

- ParaView: VARI FAIL
- Threshold 0-Idam

```
EX03
ECHO
 CONV WIN
KFIL
EROS 0.25
TRID ALE
DIME
  DEBR 5000
  NALE 1 NBLE 1
TERM
GEOM Q4GS PART 1
     T3GS PART 2
TERM
COMP
          STFL VFCC X0 -5 Y0 -5 Z0 -5
                    LX 10 LY 35 LZ 10
                    NX 40 NY 140 NZ 40! 50*50=2500 elems and 51*51=2601
                    CLX1 CLX2 CLY1 CLY2 CLZ1 CLZ2
```

```
MATE
     GAZP RO 1.3 GAMM 1.4 PINI 1.E5 PREF 1.E5
       LECT flui DIFF hpres TERM
     GAZP RO 65.0 GAMM 1.4 PINI 50.E5 PREF 1.E5
       LECT hpres TERM
     VPJC RO 7850.0 YOUN 2.1E11 NU 0.33 ELAS 3.7E8 mxit 500
          QR1 2.364E8 CR1 39.3 QR2 4.081E8 CR2 4.5
          PDOT 5.E-4 C 1.E-3 TQ 0.9 CP 452.0
          TM 1800.0 M 0.0 DC 0.9 WC 473.0E6
          LECT PART 1 PART 2 TERM
     CLVF INFI RO 1.3 PRES 1.e5 GAMA 1.4 LECT abso TERM
LINK DECO
     FLSW STRU LECT PART 1 PART 2 TERM
          FLUI LECT flui TERM
          R    0.2175 ! 0.87*H_FLUID = 0.87*0.5
          HGRI 0.401  ! > THAN BIGGER STRUCTURAL ELEMENT !!!
          DGRI
     FACE
          BFLU 2 ! BLOCK FLUXES
          FSCP 1 ! COUPLE ALONG ALL DIRECTIONS
ECRI FICH PVTK  TFREQ  0.2e-3
        GROU AUTO
        VARI ECRO DEPL VITE FAIL
OPTI NOTE
     CSTA 0.5
     LOG 1
     FLS CUB8 2 ! to avoid problem with cub8 inverse mapping ...
VFCC FCONV 6 ORDR 2
CALC TINI 0 TEND 30.0E-3
FIN
```

Flying debris

- Idea: material is in reality not eroded but mainly resulted in fragments
- Transferring the eroded elements in fragments
- Fragments were simple material points but could also be embedded in a fluid
- Drag forces and gravity could be added
- DEBR must be dimensioned at the beginning
- General debris parameters
- Creation of the debris

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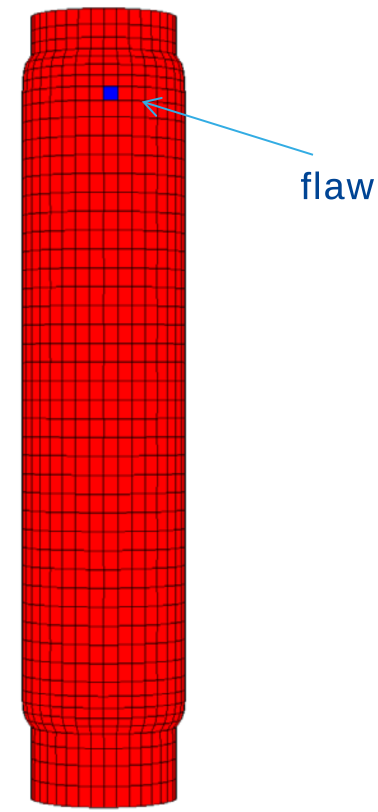
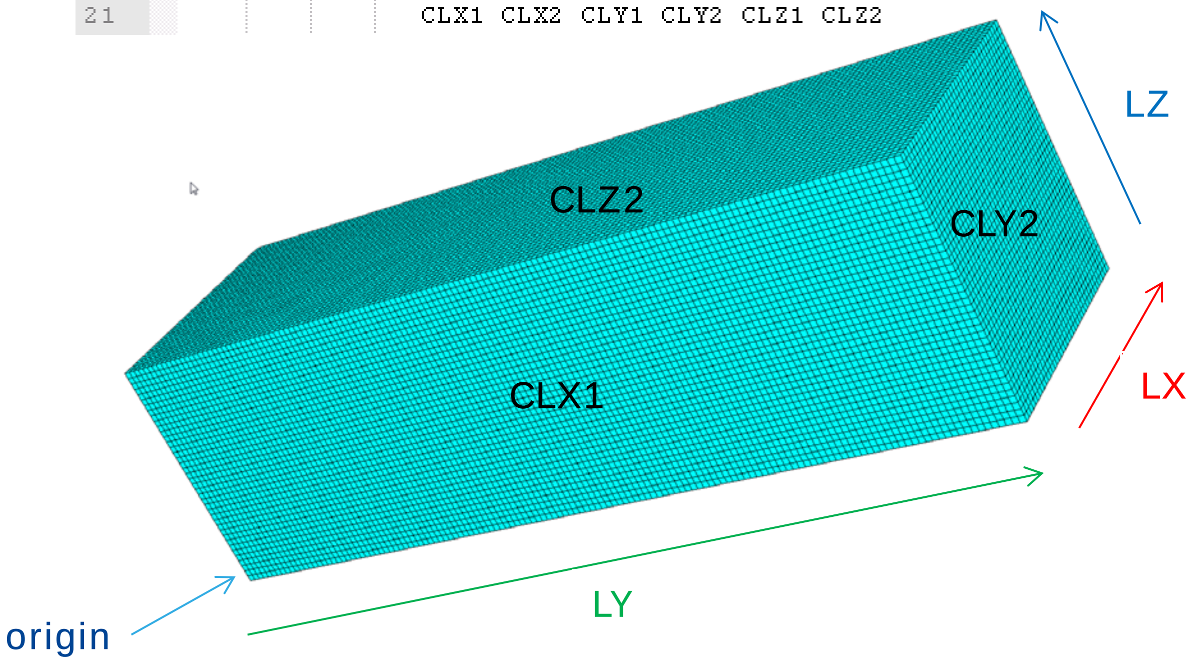
Example

FSI Inputs 3D explosion

- **Explosion of tank in open field**
  - **Embedded FLSW**
  - **Flaw inserted via a thicker element**
  - **STFL fluid mesh construction**




```
GEOM Q4GS PART 1
TERM
COMP
    STFL VFCC X0 -5 Y0 -5 Z0 -5
              LX 10 LY 35 LZ 10
              NX 40 NY 140 NZ 40
              CLX1 CLX2 CLY1 CLY2 CLZ1 CLZ2
```



FSI Inputs 3D explosion

- **Explosion of tank in open field**

```
DIME
  DEBR 31176
```

Debris definition

```
      EPAI 0.01 LECT PART 1 DIFF flaw TERM
      EPAI 0.0001 LECT flaw TERM
```

Flaw definition

```
      COUL TURQ LECT flui TERM
           ROUG LECT PART 1 DIFF flaw TERM
           VERT LECT abso TERM
           BLEU LECT flaw TERM
           JAUN LECT hpres TERM
```

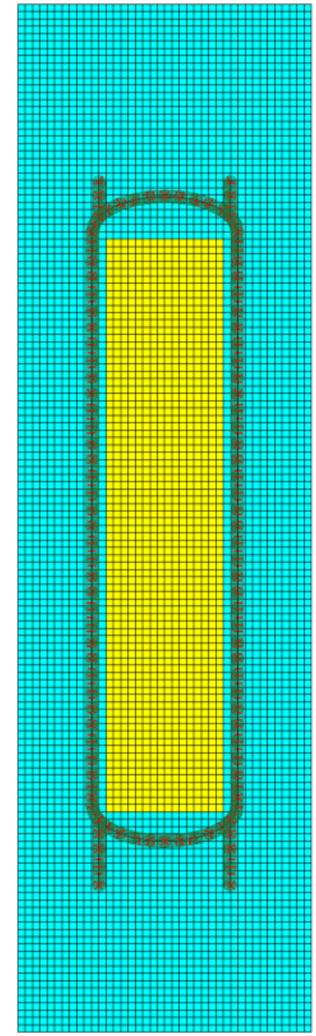
```
      DEBR
      ROF 1.0                            ! let particles move in vacuum
      FLUI LECT flui TERM HGRI 0.251 ! grid size > fluid Smesh size
      FILL PLEV 1                          ! select the level
          RO 2500 DRAG 1.0 COUP AFLY 1.0 OBJE LECT panels TERM
```

```
GRIL LAGR LECT buil _DEBR TERM
     EULE LECT flui TERM

LINK DECO
     FLSW STRU LECT PART 1 TERM
          FLUI LECT flui TERM
          R    0.2175 ! 0.87*H_FLUID = 0.87*0.25
          HGRI 0.401  ! > THAN BIGGER STRUCTURAL ELEMENT !!!
          DGRI
```

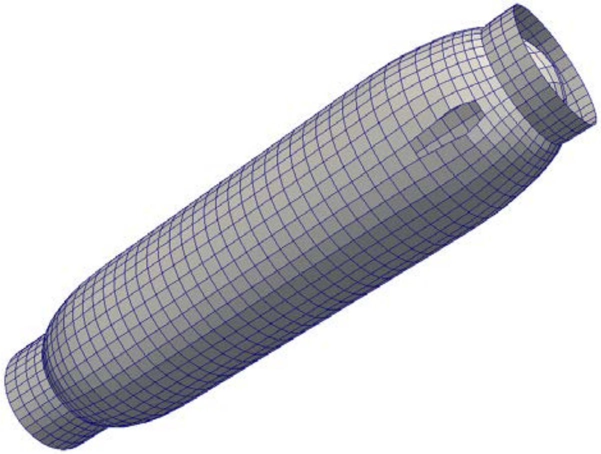
FSI parameters definition

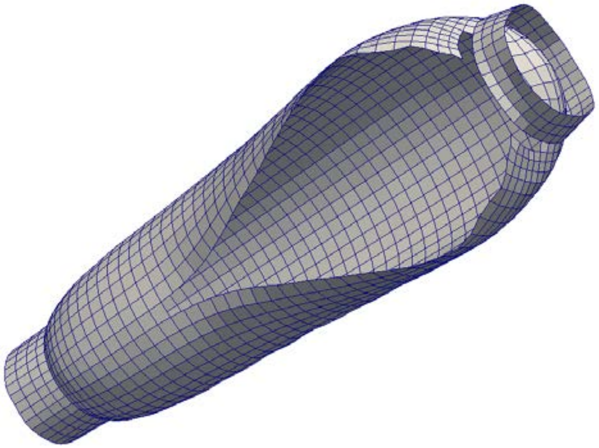
```
CHAR CONS GRAV 0.0 0.0 -9.81
                LECT _DEBR TERM ! gravity acts only on debris particles
```

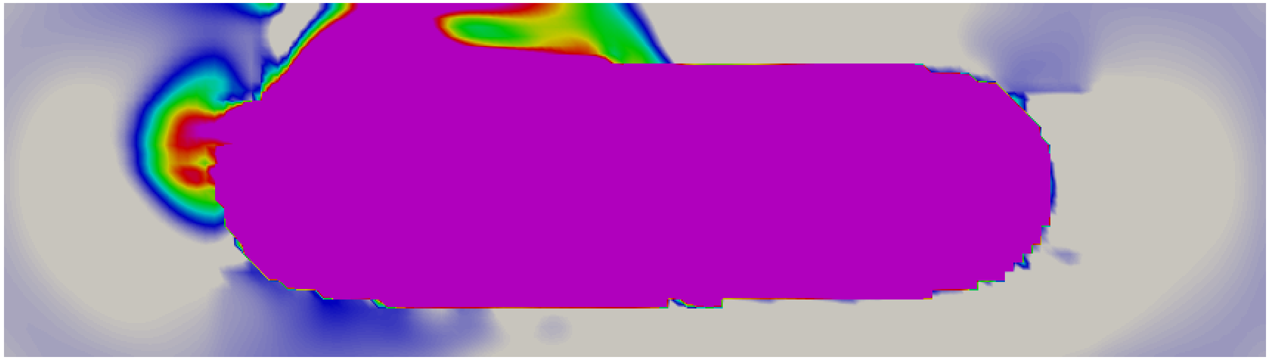


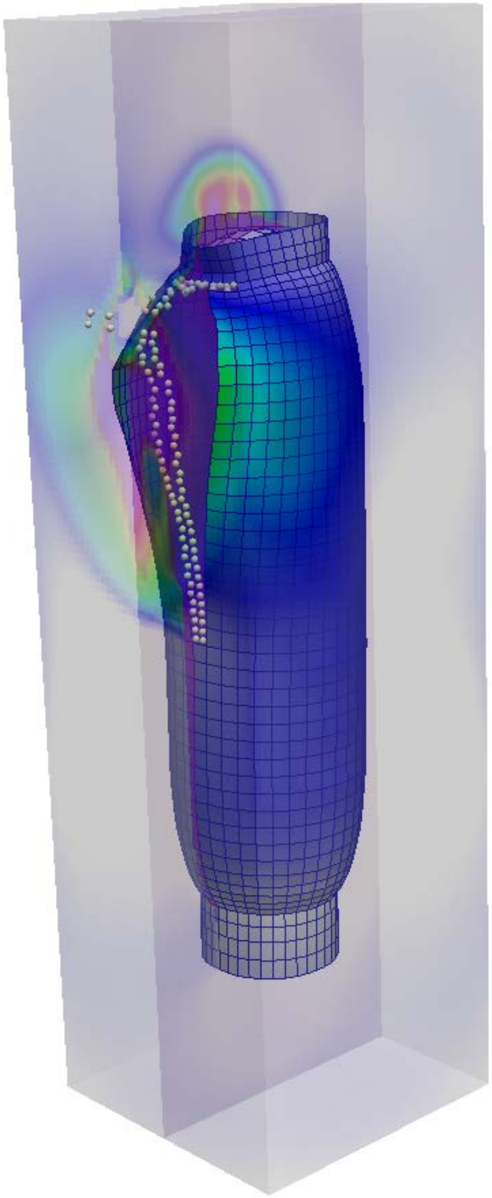
FSI Inputs 3D explosion

- **Explosion of tank in open field**
  - **Results**









- Slides\videos\Ex3An1C.avi

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FSI Inputs 3D explosion

- **Explosion of tank in open field + Adaptivity**

```
DIME
  DEBR 5000
  ADAP NPOI 50000 CUVF 30000 NVFI 100000 CL3D 50
       Q4GS 10000 ENDA
```

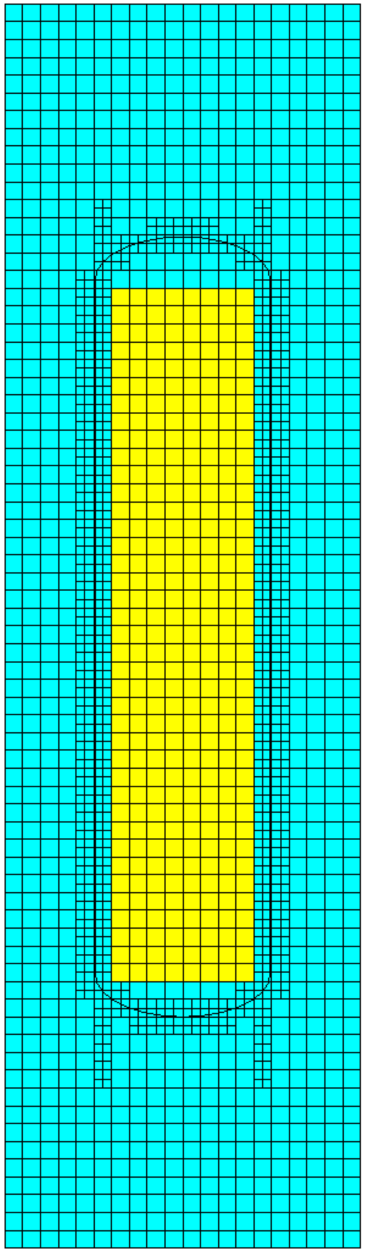
Adaptivity dimensioning

```
ADAP THRS ECRO 11 TMIN 0.45 TMAX 0.6 MAXL 3
          LECT PART 1 TERM
```

Structural refinement parameters

```
LINK DECO
     FLSW STRU LECT PART 1 PART 2 TERM
          FLUI LECT flui TERM
          R    0.425 ! 0.87*H_FLUID = 0.87*0.5
          HGRI 0.401  ! > THAN BIGGER STRUCTURAL ELEMENT !!!
          DGRI
      FACE
          BFLU 2 ! BLOCK FLUXES
          FSCP 1 ! COUPLE ALONG ALL DIRECTIONS
          ADAP LMAX 2
```

FSI refinement parameters



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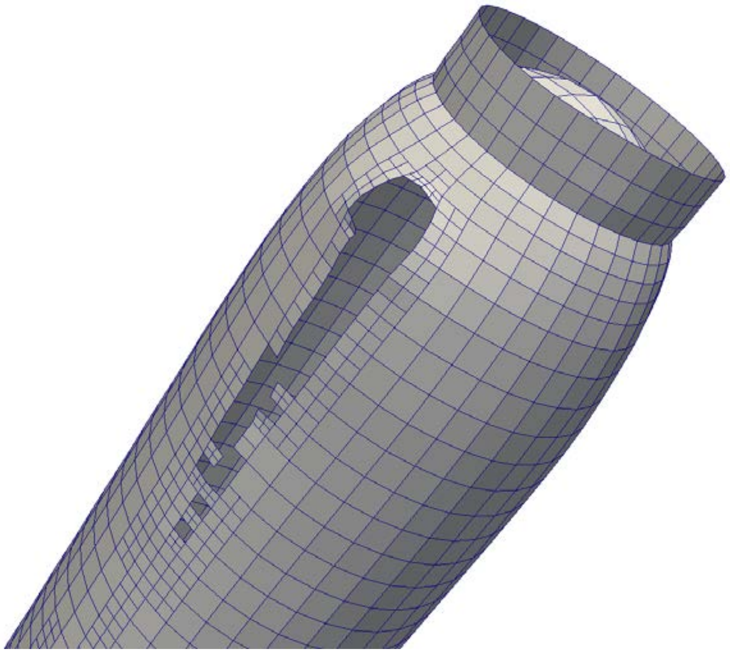
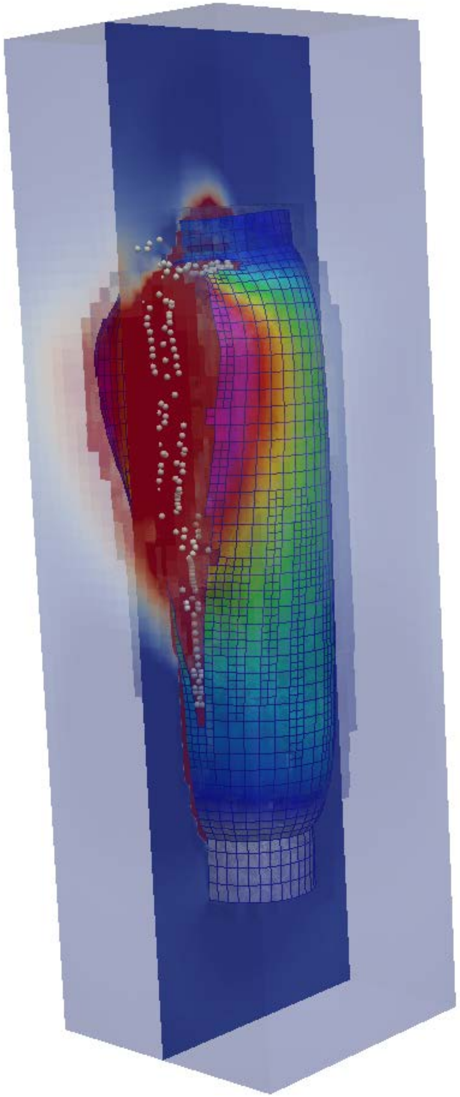
FSI Inputs 3D explosion

- **Explosion of tank in open field + Adaptivity**
  - **Results**





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fast transient dynamics • fluid-structure interaction • multiphysics

Mesh Adaptivity

Mesh adaptivity

- **Local refinement of the mesh**
  - **On some zones that considered as critical**
  - **Reduce the size of the model**
  - **High level of accuracy**

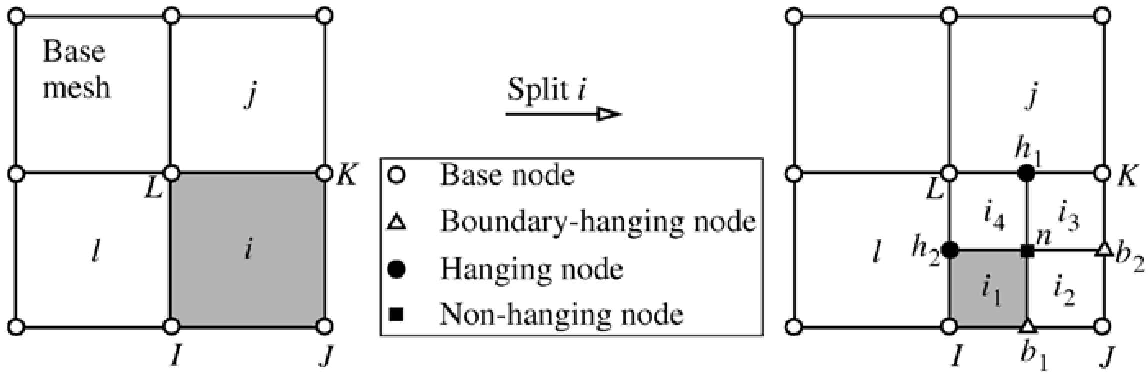


Fig. 1. Splitting a QUA4.

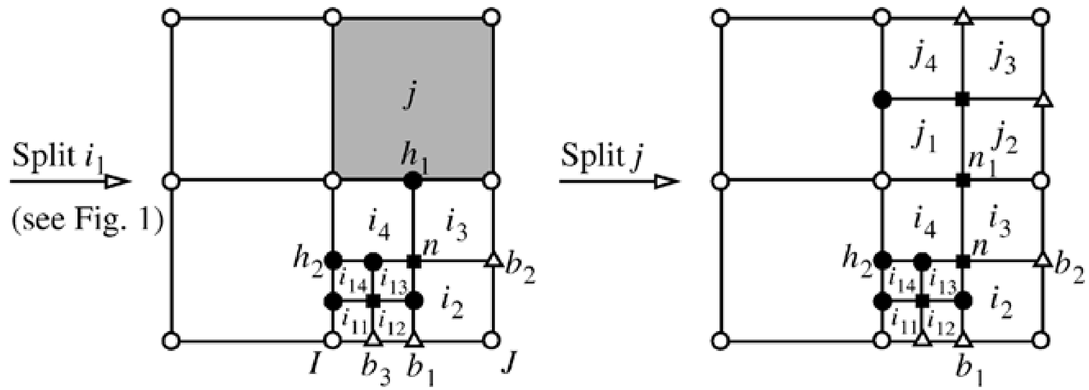
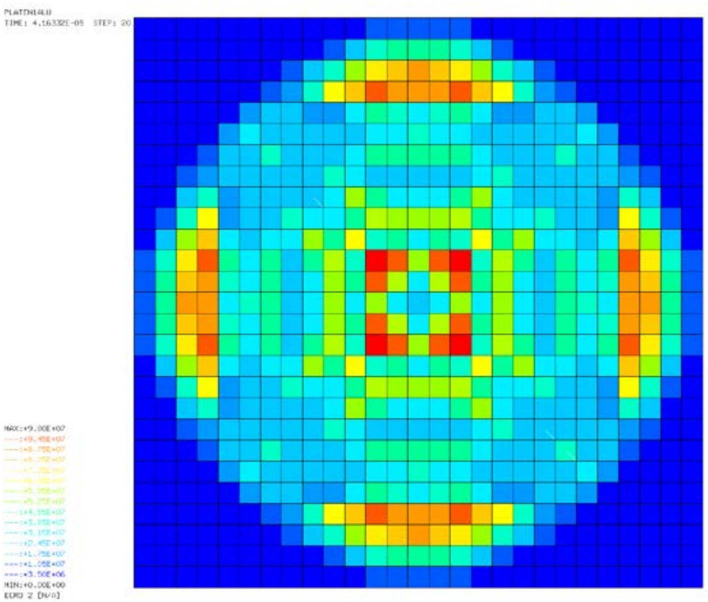
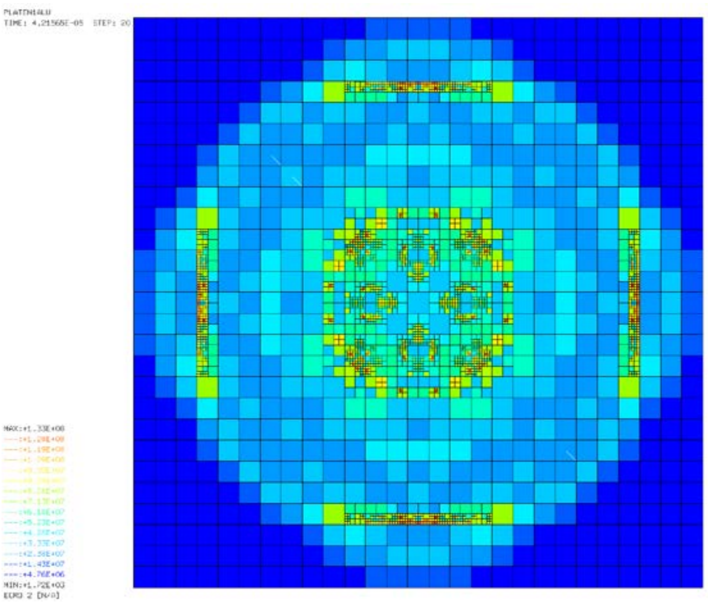


Fig. 2. Further splitting.

Structural mesh adaptivity

**ADAP THRS ECRO 2 TMIN 50e6 TMAX 100e6 MAXL 4
LECT EROA TERM**

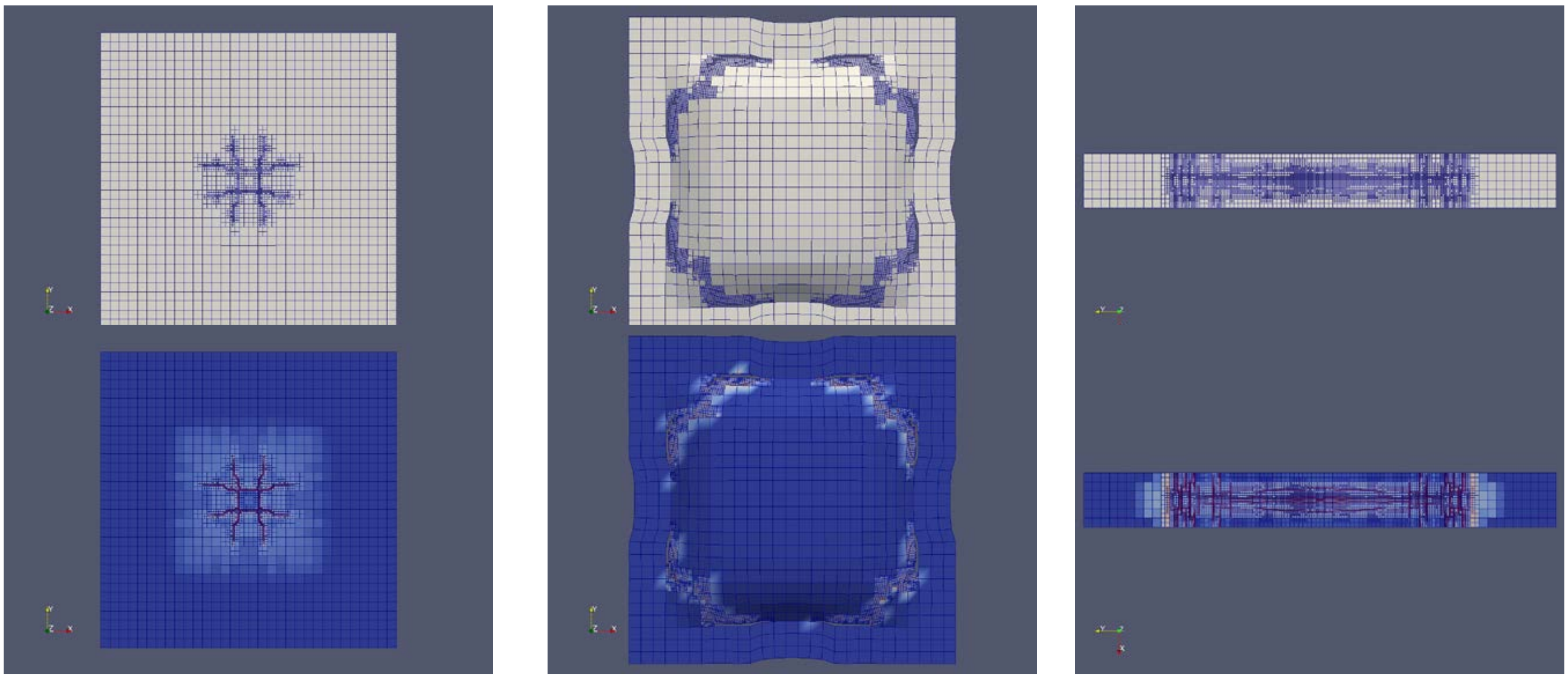




Slides\videos\A0_Glis_AdapRev2.avi Slides\videos\BAF2.avi Slides\videos\mill04_join.avi

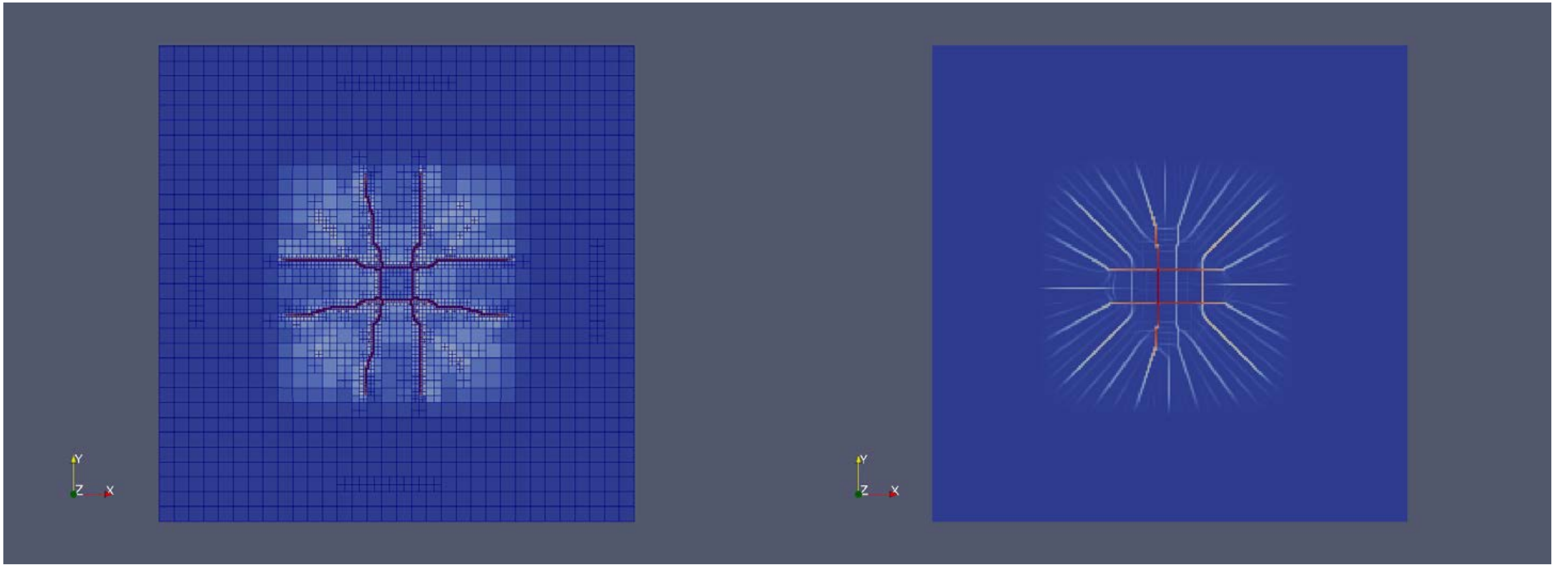
Structural mesh adaptivity

- **Crack formation with damage driven adaptivity**
  - **Indicator should be a damage parameter**
  - **No unsplit since the damage parameter is a cumulative quantity**

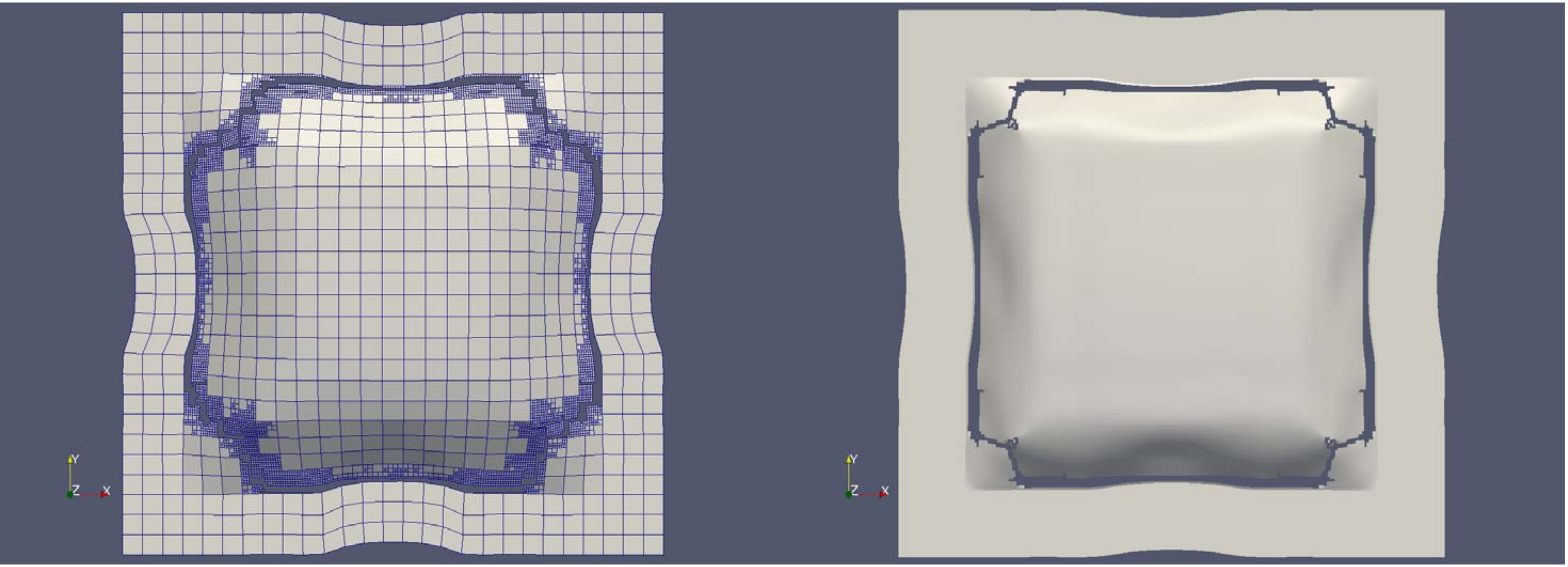


- Slides\videos\A0_Glis_AdapRev2.avi Slides\videos\BAF2.avi

Structural mesh adaptivity



Structural mesh adaptivity



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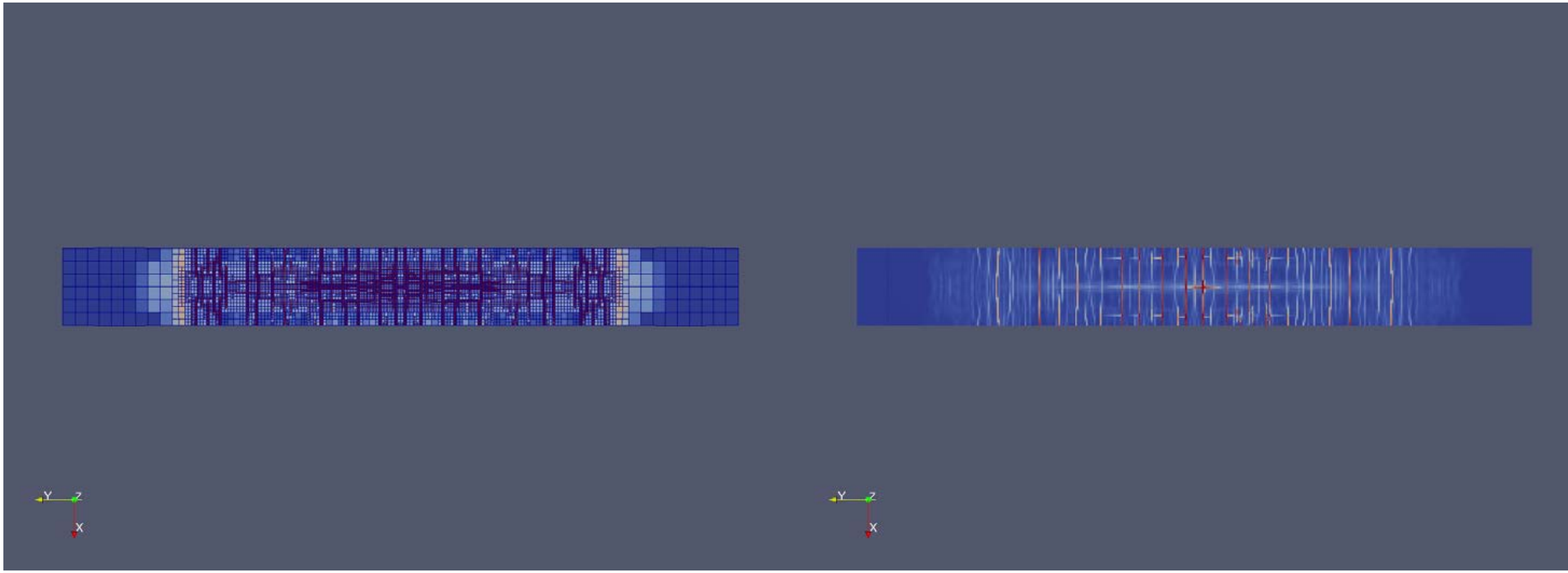
Structural mesh adaptivity



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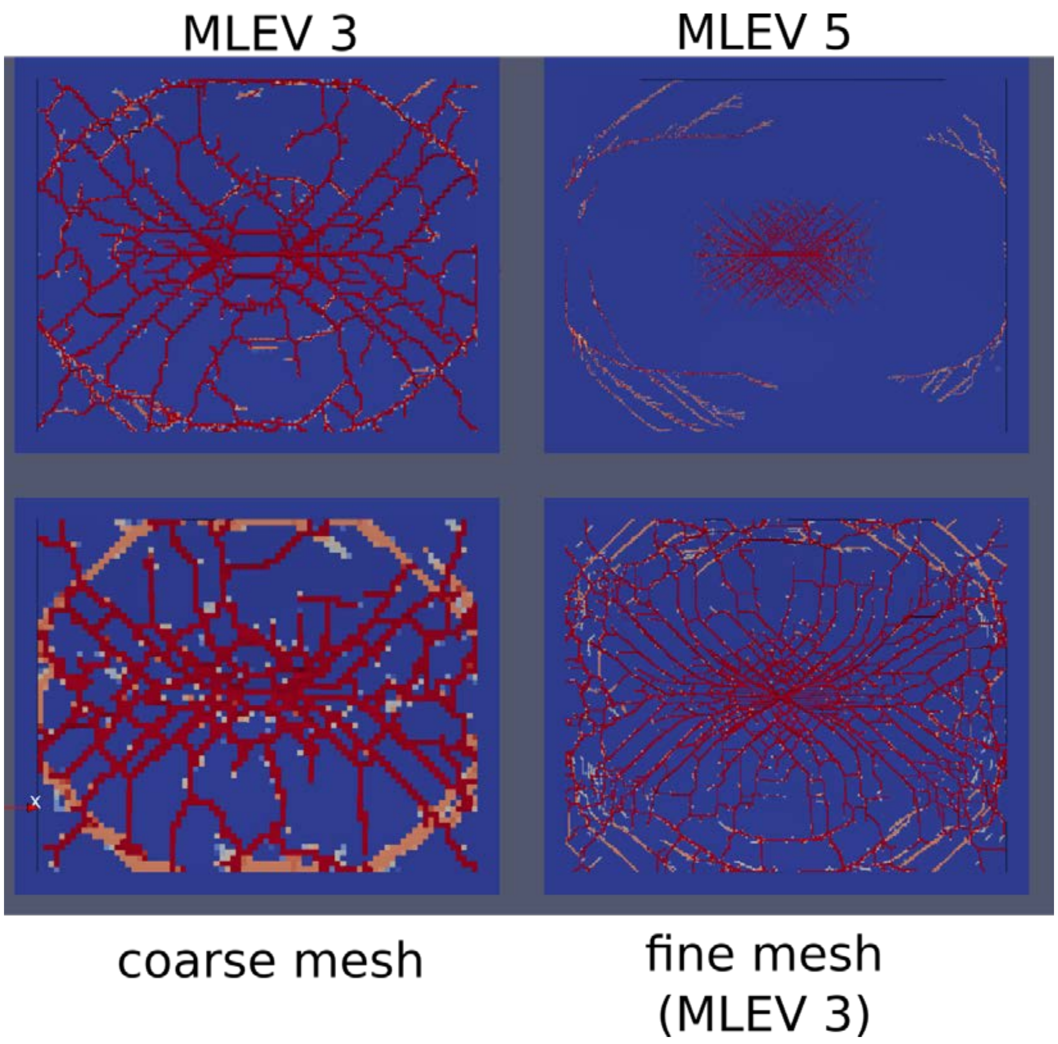
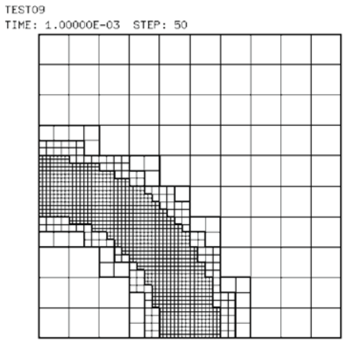
Structural mesh adaptivity

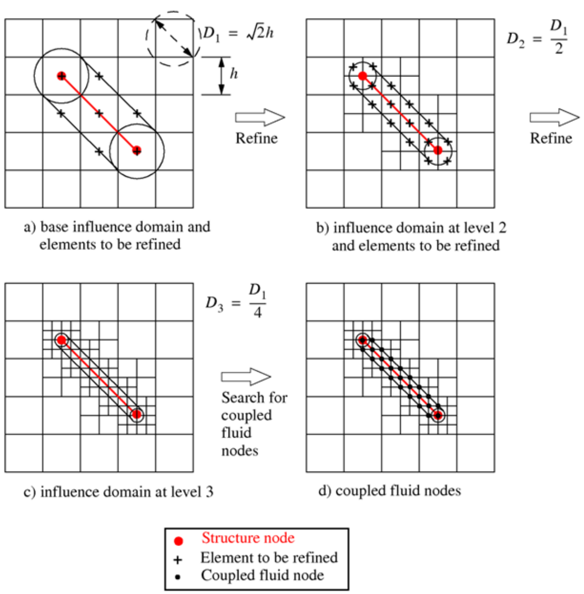


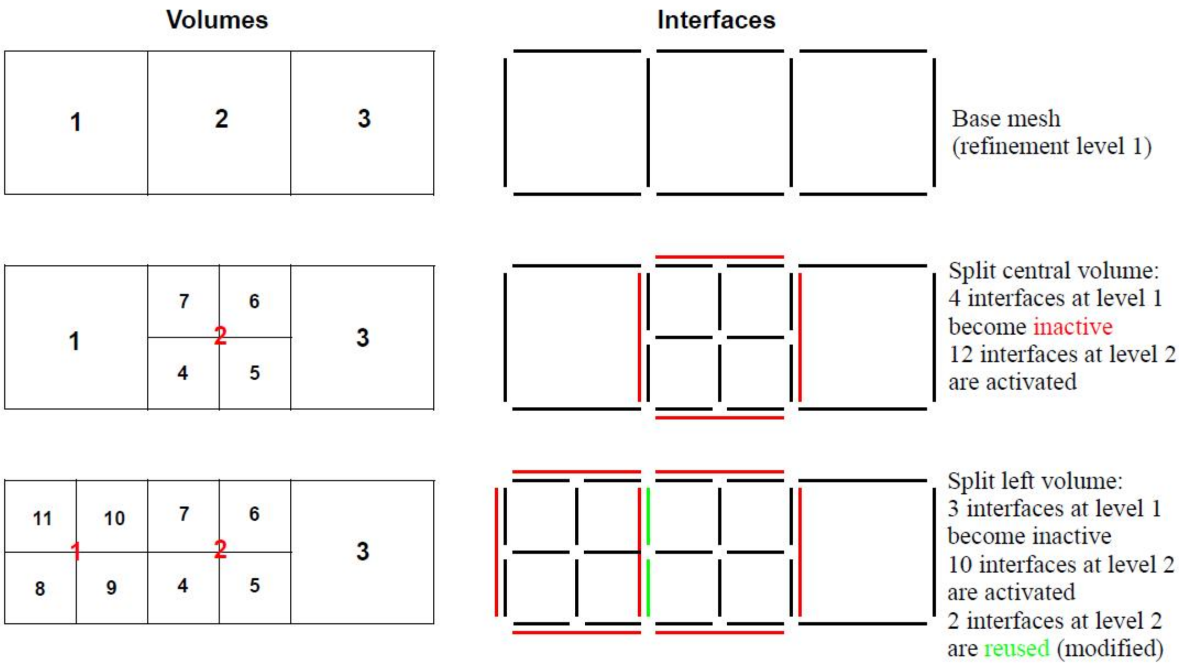
Fluid mesh adaptivity

- **Indicator driven**



- **FSI driven**





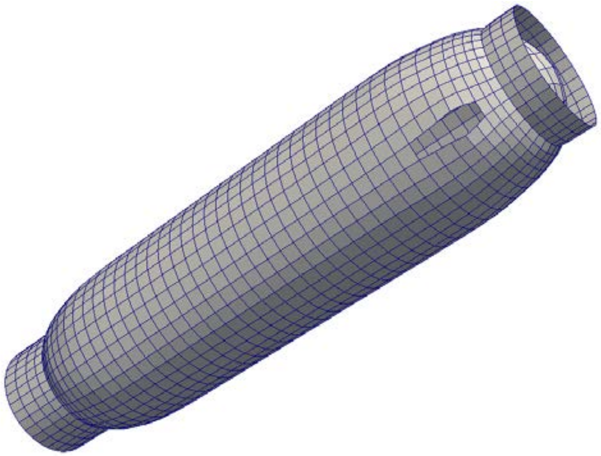
Slides\videos\fullAdaPresavi.avi Slides\videos\mill04_join.avi Slides\videos\test_adap_3d.avi

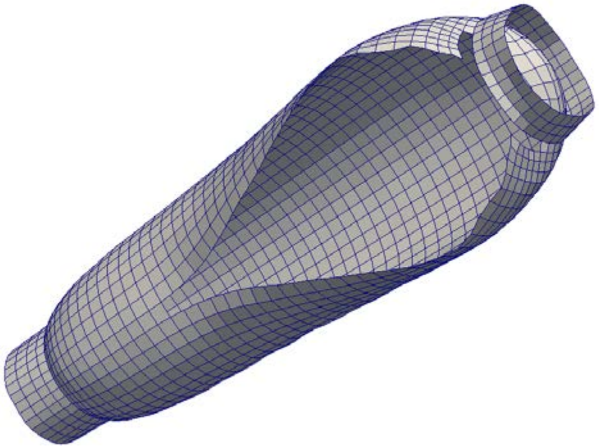
Mesh adaptivity

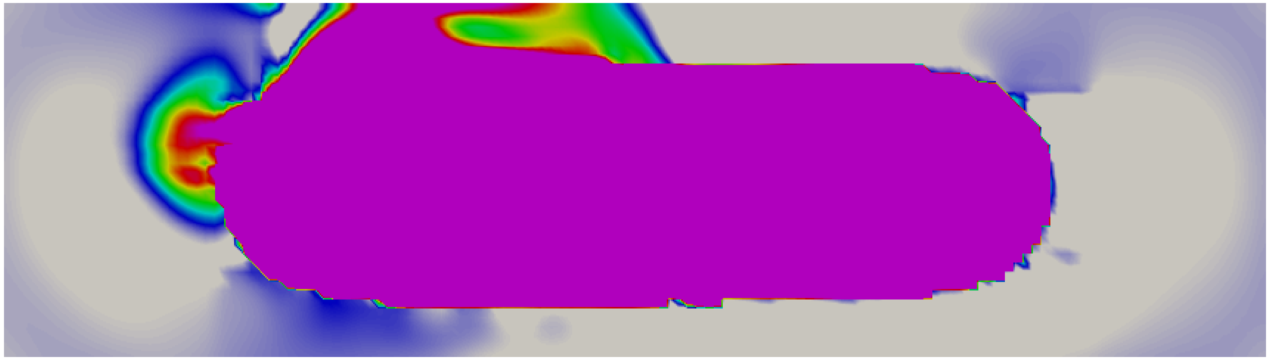
- **Advantages**
  - **Less elements → less the calculation cost**
  - **Decrease the memory requirements for the calculation**
  - **The size of the output files can decrease significantly**
  - **We can have a period with higher time step**

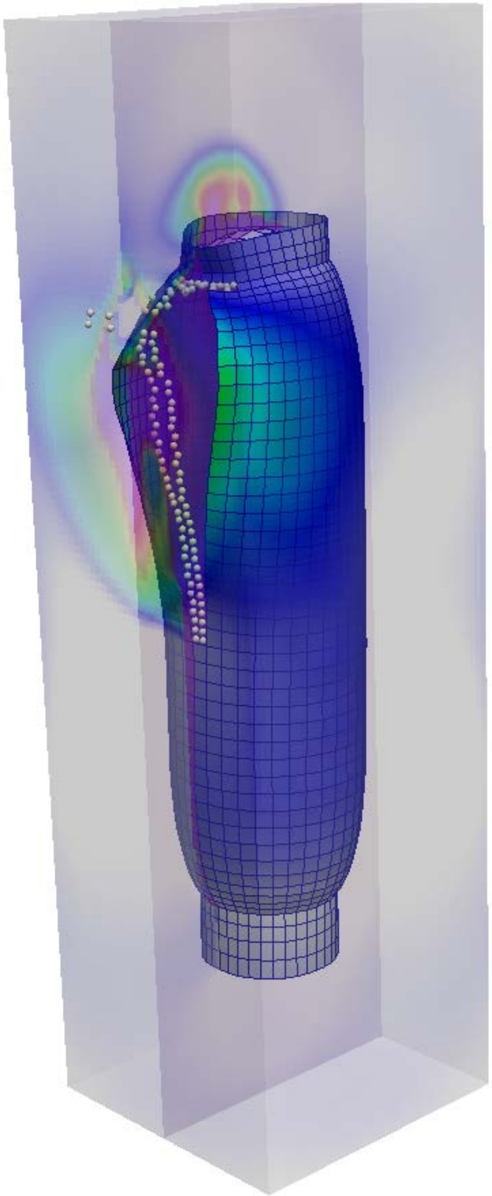
FSI Inputs 3D explosion

- **Explosion of tank in open field**
  - **Results**









- Slides\videos\Ex3An1C.avi

FSI Inputs 3D explosion

- **Explosion of tank in open field + Adaptivity**

```
DIME
  DEBR 5000
  ADAP NPOI 50000 CUVF 30000 NVFI 100000 CL3D 50
       Q4GS 10000 ENDA
```

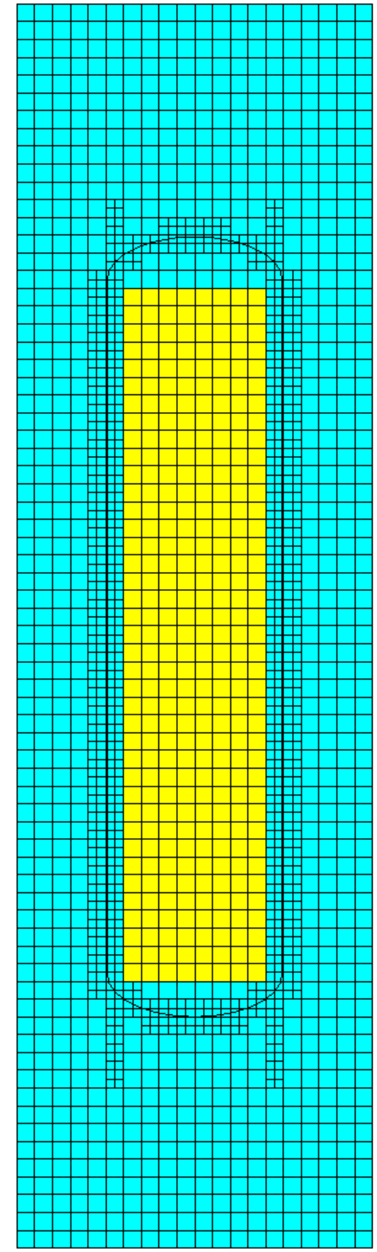
Adaptivity dimensioning

```
ADAP THRS ECRO 11 TMIN 0.45 TMAX 0.6 MAXL 3
          LECT PART 1 TERM
```

Structural refinement parameters

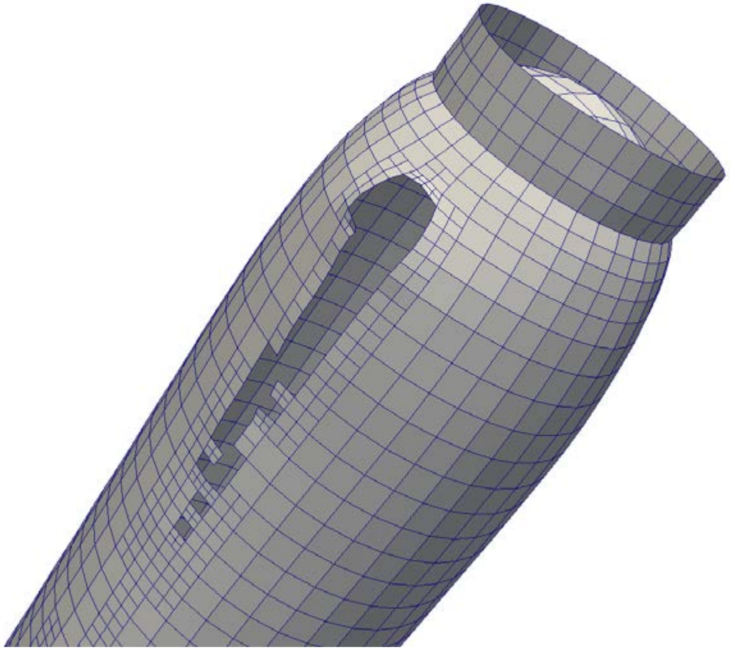
```
LINK DECO
     FLSW STRU LECT PART 1 PART 2 TERM
          FLUI LECT flui TERM
          R    0.425 ! 0.87*H_FLUID = 0.87*0.5
          HGRI 0.401  ! > THAN BIGGER STRUCTURAL ELEMENT !!!
          DGRI
      FACE
          BFLU 2 ! BLOCK FLUXES
          FSCP 1 ! COUPLE ALONG ALL DIRECTIONS
          ADAP LMAX 2
```

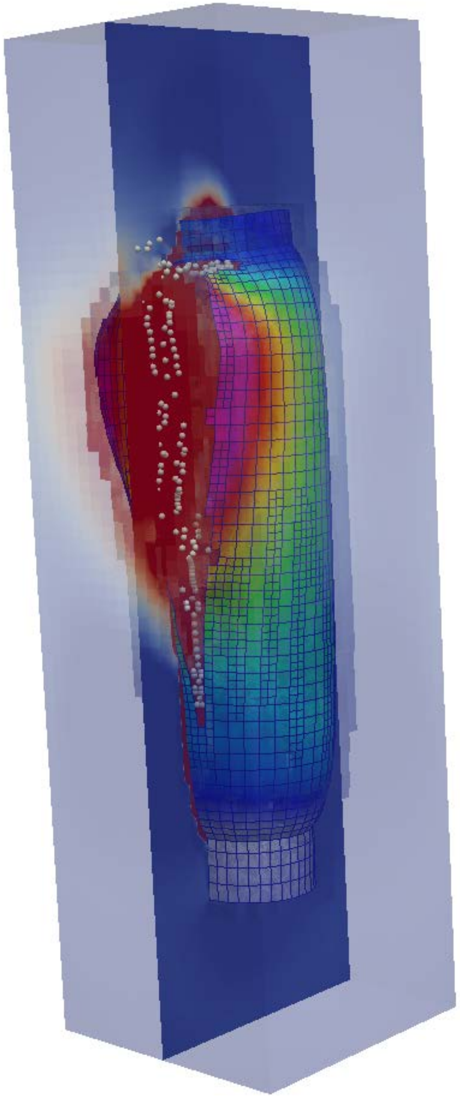
FSI refinement parameters



FSI Inputs 3D explosion

- **Explosion of tank in open field + Adaptivity**
  - **Results**





Slides\videos\Ex3An2.avi

Joint Research Centre

European Commission

Combustion

Combustion (burning)

- Chemical reaction between a fuel and oxidant
- Producing oxidized, often gaseous products

Explosions: Detonation – deflagration

- Reaction speed – speed of sound

Hydrogen explosions

$$1 \cdot H_2 + 0.5 \cdot O_2 - 1 \cdot H_2O + 0 \cdot N_2 \rightarrow 0$$

EUROPLEXUS: 2 material models GAZD and CDEM

Material models

- Euler equations (compressible, inviscid flow) for a mixture of perfect gases **in detonation regime**
- Chemical reaction represented by combustion of the hydrogen
- Associated kinetics taken into account
- Underlying equations: conservation of mass, momentum and energy, plus the equations of state of the materials and the relations describing the chemical reaction

Material models

$$H_2 + 0.5 \cdot O_2 \rightarrow H_2O$$

After a certain delay interval dT (measured from the instant at which a certain critical temperature *T* is reached) combustion starts releasing a certain amount of energy *q* into the system

Material models – GAZD ←→CDEM

- GAZD specific for detonation
- CDEM can be used for a wider range (strong detonation to weak deflagration)
- CDEM More general
- CDEM More expensive
- Course concentrates on CDEM

Material models CDEM

- At least two zones are needed: burnt and unburnt
- Each definition has two parts: general and components

General

```
MATE CDEM PINI 32.E5 ! Zone 1 (burnt)
          PREF 1.E5
          TINI 3000.
          KSI0 0.999
          K0 20000. ! Unphysically high value: the code will evaluate
          ! and use the theoretical detonation speed instead
          TMAX 6000.
          R 8.314
          NESP 4
          ORDP 4
          NLHS 2
```

Components

```
     COMP1 ! H2
          MMOL 2.E-3 H0 -4.195E6 CREA 1.0
          CV0 9.834E3 CV1 5.427E-1 CV2 8.622E-4
          CV3 -2.373E-07 CV4 1.847E-11
          YMAS 2.850E-02
     COMP2 ! O2
          MMOL 32.E-3 H0 -2.634E5 CREA 0.5
          CV0 5.750E2 CV1 3.505E-1 CV2 -1.283E-4
          CV3 2.336E-8 CV4 -1.533E-12
          YMAS 2.264E-1
     COMP3 ! H2O
          MMOL 18.E-3 H0 -1.395D7 CREA -1.0
          CV0 1.156E3 CV1 7.683E-1 CV2 -5.731E-5
          F4E_Examples.doc 01/03/15 @ 11:23
          Page 43 of 95
          CV3 -1.827E-8 CV4 2.445E-12
          YMAS 1.274E-11
     COMP4 ! N2
          MMOL 28.E-3 H0 -2.953D5 CREA 0.0
          CV0 6.529E2 CV1 2.882E-1 CV2 -7.804E-5
          CV3 8.782E-9 CV4 -3.055E-13
          YMAS 7.451E-1 ! Sum of YMAS must be 1.0
          UCDS 1 ! Limited reconstruction + UCDS
     LECT expl TERM
```

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Material models CDEM

- PINI: pressure
- PREF: reference pressure (1 bar)
- TINI: initial temperature
- KSIO: Initial volume fraction, number close to 1 but not 1.0
- K0: flame speed, chosen high, theoretical value is used
- TMAX: max temperature at which the polynomial expression giving the heat capacity at constant volume
- R: gas constant (8.314 J/(mol K))
- NESP: number of components
- ORDP: order of the polynomial equation
- NLHS: number of reactants (H2 and O2)

```
MATE CDEM PINI 32.E5 ! Zone 1 (burnt)
          PREF 1.E5
          TINI 3000.
          KSI0 0.999
          K0 20000. ! Unphysically high value: the code will evaluate
          ! and use the theoretical detonation speed instead
          TMAX 6000.
          R 8.314
          NESP 4
          ORDP 4
          NLHS 2
```

Material models CDEM

- MMOL: molar weight in kg/mol
- H0: enthalpy of formation in J/kg at T=0K
- CREA: coefficient in the reaction equation: positive for reactants, negative for products and 0 if inert

$$1 \cdot H_2 + 0.5 \cdot O_2 - 1 \cdot H_2O + 0 \cdot N_2 \rightarrow 0$$

- CV0-CV4: polynomic specific heat

$$C_V(T) = C_{V0} + C_{V1}T + C_{V2}T^2 + \cdots + C_{V\mathrm{ordp}}T^{\mathrm{ordp}}$$

- YMAS: initial mass fraction

```
COMP1 ! H2
    MMOL 2.E-3 H0 -4.195E6 CREA 1.0
    CV0 9.834E3 CV1 5.427E-1 CV2 8.622E-4
    CV3 -2.373E-07 CV4 1.847E-11
    YMAS 2.850E-02
COMP2 ! O2
    MMOL 32.E-3 H0 -2.634E5 CREA 0.5
    CV0 5.750E2 CV1 3.505E-1 CV2 -1.283E-4
    CV3 2.336E-8 CV4 -1.533E-12
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    Page 43 of 95
    CV3 -1.827E-8 CV4 2.445E-12
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    MMOL 28.E-3 H0 -2.953D5 CREA 0.0
    CV0 6.529E2 CV1 2.882E-1 CV2 -7.804E-5
    CV3 8.782E-9 CV4 -3.055E-13
    YMAS 7.451E-1 ! Sum of YMAS must be 1.0
    UCDS 1 ! Limited reconstruction + UCDS
```

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Material models CDEM: output (ECRO)

Numbering very difficult – numbering written in the listing, for 3D:

- **1: pressure of the mixture**
- **2: density of the mixture**
- **3: maximum sound speed**
- **4: Volume fraction of unburnt**
- 5: density of unburnt
- 6: x-velocity of unburnt
- 7: y-velocity of unburnt
- 8: z-velocity of unburnt
- 9: pressure of unburnt
- **10: Volume fraction of burnt**
- 11: density of burnt
- 12: x-velocity of burnt
- 13: y-velocity of burnt
- 14: z-velocity of burnt
- 15: pressure of burnt
- 22: FUNDAMENTAL FLAME SPEED
- 23: ABSOLUTE TEMPERATURE OF THE MIXTURE

...

Options

Several options

- In particular for finite volume solution

```
OPTI NOTE LOG 1
     CSTA 0.1
     VFCC RECO 3 ! Green-Gauss for CDEM/DEMS
          ERK2   ! Explicit Runge-Kutta second order time integration
          LMAS 2 ! Barth-Jesperson limiter for mass conservation
          KBAR 1 ! K is defined by barycentric coordinates
          PAS0 1.0D-12 ! Deltat at zero step
```

Easy input (!)

Definition of CDEM material only once for all parts
Some values were overwritten later on
The different parts are defined with the INIT

```
INIT ! Now we fine-tune the initial conditions
     ! for the CDEM material
     VFCC ! Initial conditions for the burnt phase
          VITX 0.0
          VITY 0.0
          VITZ 0.0
          PINI 32.E5
          TINI 3000.0
          KSI0 0.999
          K0 20000. ! Unphysically high value: the code will evaluate
                    ! and use the theoretical detonation speed instead.
          Y1 2.850E-02
          Y2 2.264E-1
          Y3 1.274E-11
          Y4 7.451E-1
          LECT H2_burnt TERM ! "burnt" is the name of the mesh zone
                                  ! initially containing (mostly) the burnt phase
```

Examples